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17 Abstract

The purpose of this study was to develop a set of criteria for airline passenger protective breathing equipment, to determine whether any existing emergency smoke mask meets the criteria, and if not, recommend direction for subsequent criteria research and/or development. After a review of existing standards and regulations, criteria and test protocols were developed for: edge leakage, smoke and toxic gas penetration, condition of inhaled air, ease of donning, vision and communication and breathing resistance. Six candidate masks were evaluated using the test protocol. Further development is recommended in the areas of vision and communication, breathing resistance, particulate edge leakage, resistance to flame and selection of test subjects.

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17. Résumé

Le but de cette étude était de développer un nombre de critères concernant l'équipement de protection respiratoire pour passagers d'avion, de déterminer s'il existait des masques de protection contre la fumée satisfaisant à ces critères et, dans la négative de recommander une ligne directrice pour la recherche et/ou le développement subséquent à de tels critères.

Après examen des normes et des règlements existants, des critères et des protocoles d'essais ont été définis pour: fuite, pénétration de fumée et de gaz toxiques, état de l'air inspiré, facilité de mise en place, vision et communication, ainsi que pour la résistance à l'inhalation.

Six masques ont été évalués suivant les protocoles d'essai. Des améliorations sont nécessaires quant à la vision et à la communication, à la résistance à l'inhalation ainsi qu'à l'ingression pariétale des particules de fumée, et à la résistance aux flammes. La sélection des sujets pour les essais doit faire l'objet d'une attention particulière.

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SUMMARY

The concept of providing respiratory protection to airline passengers to allow escape from burning aircraft is not new. The idea was studied as early as 1967.[15] In 1969, in fact, the U.S. Federal Aviation Administration (FAA) issued Notice of Proposed Rule Making (NPRM) 69-2 which proposed the use of smoke hoods to provide airline passengers with respiratory protection in the case of fire. However, the notice was withdrawn on the grounds that use of smoke hoods could delay emergency evacuation.[16] Recent tragedies, however, such as the Cincinnati DC-9 fire in 1983 and the Manchester Boeing 737 fire in 1985, have refocussed public attention on the issue of passenger cabin safety in general and passenger respiratory protection in particular.[17,18]

Passenger aircraft fires involving risk to life can be classified as either post-crash or in-flight fires. Post-crash fires generally develop as a result of ignition of jet fuel released from storage tanks damaged by the crash. They are characterized by high radiant heat loads, some damage to the fuselage and relatively short periods of time to the flash-over condition. Flash-over involves the rapid growth of the fire from an area in the immediate vicinity of the fuel fire to the remaining cabin interior. It is not considered realistic to provide survival beyond the flash-over point.

The key to survival in post-crash fires is rapid evacuation of the cabin; the FAA[16] points out that anything delaying evacuation, such as the need to don a smoke mask, may be detrimental to survival.

The major thrust of FAA activities to enhance passenger survivability in cabin fire situations has been to fire-harden the cabin

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interior and develop improved methods of smoke evacuation in flight. Whilst mandating the carriage of smoke masks is not being considered by the FAA, new design and design standards will be considered for possible inclusion in a Technical Standard Order should the industry decide to pursue the matter.[20]

In-flight fires usually occur in accessible areas such as galleys and are detected and extinguished promptly. On rare occasions they may also occur in inaccessible areas such as the baggage compartment. Such fires are characterized by low heat loads and a relatively long period of time to flash-over.

The key to survival in an in-flight fire is immediate landing of the aircraft and evacuation. The time required to make an emergency landing depends on the proximity of an acceptable landing area and is in the order of 15 minutes over continental North America. In the Cincinnati accident, approximately 20 minutes elapsed between the discovery of the fire and landing of the aircraft.[24] Of paramount importance, therefore, is the protection of respiration and vision and maintenance of occupants in a conscious and mobile state such that they can evacuate once the aircraft has landed.

This study was conducted with the following objectives:

1. To produce a set of criteria for airline passenger protective breathing equipment,

2. To determine whether any existing emergency smoke masks meet these criteria and,

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3. If necessary, to recommend the direction for subsequent research and/or development.

There are currently no standards for airline passenger smoke masks. The most thorough respirator standards in existence are those relating to the field of industrial occupational health. Industrial use, however, is wholly different from emergency escape use. Industrial respirators are designed to protect the wearer from both the long-term and acute effects of a narrow range of contaminants. Users are trained in their use and operation and are knowledgeable in the hazards to which they may be exposed. Emergency smoke masks are designed for a one-time use by people unfamiliar with them and untrained in their use. They are designed to protect against incapacitation for a relatively short time period in the unpredictable environment of a fire.

After a review of industrial standards, draft standards for emergency escape smoke masks, and regulations covering protective breathing equipment for airline flight crews, criteria and test protocols were developed based on the British Standards Institute (BSI) draft standard on emergency escape masks[1]. The following main topics were addressed:

- Edge leakage
- Smoke and Toxic Gas Penetration
- Condition of Inhaled Air
- Ease of Donning
- Vision and Vocal Communication
- Breathing Resistance

In order to test available emergency escape smoke masks against the developed test protocol a search of the equipment market and

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scientific and patent data bases was conducted. A wide variety of protection concepts were identified. Of twenty-four smoke masks identified, six were selected for inclusion in the test program. Masks were rejected if they were not available commercially or were still in an initial development stage. The following candidate smoke masks were selected and tested:

- Vivat Mask
- PELS System
- Smokefighter
- Parat Mask
- S-Cape Hood
- Safeaire Hood

Even though none of the six candidate smoke masks met the criteria, various good design concepts were identified. The rubber and silicon neck seals provide satisfactory edge leakage protection; filtration systems are capable of providing toxic gas removal; compounds are available for removing CO_2 from exhaled air; and, the smoke masks can be donned in less than 15 seconds. Further details on the candidate smoke mask evaluation tests are summarized as follows:

Edge Leakage

The test protocol for measuring edge leakage successfully quantified the degree of edge leakage of gases into both the breathing and the ocular zones. Only two of the candidate smoke masks met an edge leakage criteria of 5% in the breathing zone and 10% in the ocular zone. These smoke masks had silicon and rubber neck seals.

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Smoke and Toxic Gas Penetration

Manufacturer test data was used to evaluate smoke and toxic gas penetration. Three of the five candidate smoke masks which employed filtration systems to provide clean breathing air satisfied the toxic gas removal criteria. Two of the smoke masks do not have the provision for carbon monoxide removal, and therefore, did not meet the criteria.

Condition of Inhaled Air

The test protocol for measuring the condition of the inhaled air successfully quantified the levels of O_2, CO_2 and temperature within the smoke masks. Two of the six masks experienced CO_2 levels greater than a criterion maximum level of 3%. However, only when CO_2 levels exceeded 4% did the subjects experience extreme discomfort and terminate the tests.

Ease of Donning

The time to don the masks ranged from 3 to 18 seconds and averaged 10 seconds as compared to a criterion of 15 seconds.

Vision and Communication

Two of the six candidate masks did not meet the vision criterion and one of the six did not meet the vocal communication criterion.

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Breathing Resistance

All candidate masks satisfied an inhalation resistance criterion of 8 mbar and an exhalation resistance criterion of 3 mbar. However, one mask experienced high CO_2 and another high edge leakage, both of which were due to filter breathing resistance. Test subjects also perceived discomforting high pressure resistance in two candidate smoke masks during the edge leakage and condition of inhaled air tests.

Based on the smoke mask evaluation tests, the following recommendations regarding further development of passenger airline protective breathing equipment performance criteria are presented.

An airborne particulate test protocol should be developed and tested on candidate smoke masks. The edge leakage test criterion developed in this study uses a tracer gas. It is not known whether the tracer gas edge leakage results are representative of fire particulate edge leakage.

Test subjects for this program did not include the young, the old or those with respiratory illnesses. Test subject selection criteria should be developed to include those representative of airline passengers.

The vision and vocal communication criteria and test protocols were overly simplistic. More quantitative criteria and test protocols should be developed.

Further research is needed to determine filter pressure drops which adversely affect the performance of a smoke mask or are unacceptably discomforting to the wearer.

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It is recommended that Federal Aviation Regulation 25.853 and Underwriters Laboratory Test 94 be evaluated with regards to their suitability as resistance to flame criteria.

In order to assess protection from inhalation incapacitation, a methodology should be developed to determine a smoke mask protection factor. This methodology could be based on the results of the tests for edge leakage, conditions of inhaled air, and smoke and toxic gas penetration.

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SOMMAIRE

Le concept de la protection respiratoire pour les passagers des transports aériens afin de leur permettre de fuir lors d'un incendie, n'est pas nouveau. L'idée en a été étudiée des 1967[15]. En 1969, l'Administration fédérale américaine de l'aviation (FAA) publiait une notification d'une proposition de règlement (NPRM 69-211) qui suggérait l'utilisation de cagoules anti-fumée pour la protection respiratoire des passagers en cas d'incendie. Cependant cette notification a été retirée alléguant qu'un tel usage ralentirait l'évacuation d'urgence des avions[16]. Des tragédies récentes, telles que l'incendie en vol à bord du DC 9 de Cincinnati, en 1983, et celui, au sol, du Boeing 737 à Manchester en 1985, ont rappelé l'insuffisance des moyens de protection des passagers, et particulièrement concernant la protection respiratoire[17,18].

Les incendies à bord des avions comportant le plus de risques pour la vie des passagers sont ceux qui se produisent en vol ou au sol, après un accident. Ceux-ci sont généralement dus à l'inflammation du carburant à la suite de la rupture des réservoirs. Ils se caractérisent par un rayonnement intense et par une période relativement courte, lorsque le fuselage est peu endommagé, avant que l'atmosphère de la cabine ne s'enflamme spontanément. Cette inflammation résulte de la propagation rapide du feu de sa source initiale au matériel contenu dans la cabine. La protection respiratoire devient alors superflue.

La survie des passagers suite à un incendie après un accident ne peut être assurée que par une évacuation rapide de la cabine; le FAA[16] a fait remarquer que tout retard dans l'évacuation, tel que la mise en place d'un masque anti-fumée, peut aussi réduire les chances de survie.

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L'effort principal du FAA afin d'assurer la survie des passagers lors d'un incendie dans la cabine a porté sur l'utilisation de matériaux enflammables à l'intérieur de la cabine, ainsi que sur l'évacuation des fumées lorsque l'avion est en vol. Bien que le FAA ne veuille pas rendre obligatoire la présence de masques anti-fumée à bord des avions, il étudiera les nouveaux concepts ainsi que les normes de fabrication afin de les inclure dans un "Technical Standard Order" si l'industrie désire poursuivre cette technologie[20].

Les incendies en vol se produisent généralement dans des endroits accessibles, tels que les cuisinettes, et sont alors promptement détectés et éteints. Plus rarement, ils peuvent survenir dans des endroits inaccessibles, tels que les compartiments à bagages. Il s'agit là de feux couvants, avec peu de dégagement de chaleur, et il s'écoule un laps de temps relativement long avant l'inflammation globale.

Les chances de survie dans de tels cas dépendent de l'atterrissage immédiat suivi d'une évacuation rapide de l'avion. Le temps nécessaire à un atterrissage d'urgence dépend évidemment de la proximité d'un terrain adéquat. Sur le continent nord-américain ce temps est de l'ordre de 15 minutes. Lors de l'accident de Cincinnati l'atterrissage a eu lieu environ 20 minutes après la découverte de l'incendie[24]. Ainsi, il est primordial de protéger le système respiratoire des passagers afin qu'ils puissent évacuer l'avion par leurs propres moyens lors de l'atterrissage.

Cette étude a été faite en vue de:

1. Etablir des critères concernant l'équipement de protection respiratoire pour les passagers d'avion de ligne;

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2. Déterminer s'il existe des masques de secours anti-fumée rencontrant ces critères; et,

3. Si nécessaire, recommander la marche à suivre pour les recherches et/ou les devéloppements ultérieurs.

Il n'existe présentement aucune norme publiée sur les masques anti-fumée pour les passagers d'avion de ligne. Par contre, de telles normes sont en vigueur dans le secteur industriel. Cependant, dans ce cas, le masque est conçu pour protéger, à court et à long terme, son utilisateur contre des contaminants spécifiques. De plus, l'utilisateur est entraîné à son usage et connaît les risques encourus. La situation est toutefois différente pour les passagers d'avion qui ne sont ni familiers avec l'équipement, ni entraîné à cet usage. Le masque doit protéger, à très court terme, contre l'incapacitation du passager dans l'environnement dangereux et imprévisible d'un incendie.

La présente étude a défini des critères pour masques anti-fumée et des protocoles d'essais après un examen de normes industrielles, de propositions de normes pour des masques d'urgence et des règlements en vigueur concernant l'équipement respiratoire des équipages d'avion de ligne. Ces critères et protocoles sont basés sur une proposition de normes préparées par le "British Standards Institute" (BSI)[1]. Les points suivants ont semblé les plus importants:

- Fuite pariétale
- Filtration de fumée et de gaz toxiques
- Qualité de l'air
- Facilite d'utilisation
- Vision et communication
- Résistance respiratoire

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Afin de procéder aux essais des masques selon les protocoles choisis, une recherche a été effectuée pour identifier l'équipement disponible, les données scientifiques pertinentes et les brevets existants. Un grand nombre de concepts ont été découverts. Des vingt-quatre masques identifiés, six ont été retenus pour le programme d'essai. Les masques rejetés l'ont été parce que non disponibles dans le commerce ou encore en période de développement. Ceux qui ont été retenus sont:

- Masque de secours VIVAT
- Système PELS
- Masque SMOKEFIGHTER
- Masque PARAT
- Cagoule S-CAPE
- Cagoule SAFEAIRE

Même si aucun des six masques retenus n'a rencontré les critères, on a pu identifier des concepts intéressants. Par exemple, les collerettes en silicone ou en caoutchouc scellent correctement contre les fuites; les filtres sont efficaces contre les gaz toxiques; il existe des produits capables d'absorber le CO_2 de l'air exhalé et les masques peuvent être mis en moins de 15 secondes. Les essais sur les masques retenus se résument comme suit:

Fuite pariétale

Le protocole d'essai pour cette caractéristique a permis la mesure de l'ingression des gaz à l'intérieur des zone oculaire et respiratoire

des masques. Seulement deux des masques à l'essai ont respecté les critères choisis, soit 5% dans la zone respiratoire et 10% dans la zone oculaire. Ces masques possédaient des collerettes de silicone ou de caoutchouc.

Filtration de fumée et de gaz toxiques

Les essais des manufacturiers ont été utilsés pour cette évaluation. Trois des cinq masques utilisant des filtres à air ont rencontré les critères. Deux des masques n'éliminaient pas le monoxyde de carbone et, par conséquent, n'ont pas respecté les critères.

Qualité de l'air

Le protocole d'essais a permis de mesurer les concentrations de O_2 et de CO_2 à l'intérieur du masque ainsi que la température de l'air. Tous les six masques ont obtenus des concentrations de CO_2 supérieures au critère fixé à 3%. Cependant, c'est seulement lorsque cette concentration a dépassé 4% que les volontaires ont été fortement incommodés et ont dû cesser les essais.

Facilité d'utilisation

Le temps requis pour adjuster les masques s'étale de 3 à 18 secondes, avec une moyenne de 10 secondes. Le critère choisi est de 15 secondes.

Vision et communication

Deux des six masques retenus n'ont pas rencontré le critère de vision et un seul n'a pas respecté celui de la communication vocale.

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Résistance respiratoire

Tous les masques ont satisfait aux critères de résistance choisis qui étaient de 8 mbar de pression différentielle pour l'inhalation et 3 mbar pour l'exhalation. Cependant, l'un des masques avait une forte concentration de CO_2 et un autre des fuites pariétales importantes, deux défauts créés par une résistance respiratoire élevée. De plus, des volontaires ont été incommodés par la résistance respiratoire de deux des masques durant les essais de fuite pariétale et de qualité de l'air.

A la suite des essais les recommandations suivantes ont été faites concernant le développement de critères de performance pour l'équipement de protection respiratoire des passagers des transport aériens.

Un protocole d'essai pour les particules de fumée devra être étudié. En effet, l'essai de fuite pariétale utilise un gaz très dilué. On ne sait si la diffusion de ce gaz représente bien le comportement des particules de fumée.

Les volontaires utilisés pour ce programme ne comprenaient pas de sujets très jeunes ou âgés, ou ayant des difficultés respiratoires. L'échantillonnage des sujets choisis devra être plus représentatif de celui des passagers des lignes aériennes.

Les critères de vision et de communication vocale choisis étaient trop simplistes. Des critères quantitatifs et des protocoles d'essais adéquats devront être dévelopés.

Des recherches supplémentaires sont requises pour determiner le niveau critique de perte de charge à travers les filtres à partir duquel les performances d'un masque se détériorent ou son port devient intolérable.

On recommande que le "Federal Aviation Regulation" 25.853 et l'essai "Underwriters Laboratory" 94 soient évalués comme critères pour la résistance aux flammes.

Dans le but de mesurer la protection des masques contre l'incapacitation respiratoire, il est recommandé de développer une méthode permettant de définir un facteur global de protection. Cette méthode pourrait être basée sur les résultats d'essais portant sur les fuites pariétales, la qualité de l'air inspiré et la pénétration des fumées et des gaz toxiques.

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1. INTRODUCTION

1.1 Objectives

The objectives of this study were as follows:

1. To produce a set of criteria for airline passenger protective breathing equipment. For the sake of simplicity, the term "smoke masks" will be used in place of "airline passenger protective breathing equipment", for the remainder of this report,

2. To determine whether any existing smoke mask meets these criteria, and,

3. If necessary, to recommend the direction of subsequent research and/or development,

1.2 Study Methodology

This report provides a review of aircraft fire safety, and the role of smoke masks in aircraft fire safety, presents a set of smoke mask evaluation criteria and test protocols and reports on the results of testing six candidate smoke masks.

Work was initiated with a review of on-going work in North America and elsewhere on aircraft fire safety through a literature search and by contact with individuals active in the area. Primary attention was given to passenger respiratory protection and smoke mask test

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procedures. Based on this review, a set of criteria and test protocols were developed. The criteria and test protocols are based on the British Standards Institute (BSI) draft emergency escape mask specification[1] and the U.S. Federal Aviation Administration (FAA) Technical Standard Order C99[2].

In order to determine whether any existing mask meets these criteria an extensive search of the equipment market and scientific and patent data bases was conducted followed by testing of six candidate smoke masks. Each of the six smoke masks was evaluated against six main criteria topics. Results of the tests are presented and both the performance of the smoke masks and the suitability of the criteria are discussed. Based on these findings, recommendations for subsequent research and/or development are presented.

1.3 Background

The concern over aircraft fire safety is well-founded. The cabins of passenger aircraft are typically cramped and crowded. In addition, they are composed of a wide variety of organic and polymeric materials capable of undergoing thermal decomposition and flaming combustion. These include structural and decorative molded plastics, panelling and interior finishing, foam seat cushions, upholstery, carpets, blankets, luggage, natural and synthetic clothing and a number of other materials. Most cabin interior materials are able to resist small ignition sources, but they readily decompose and burn when exposed to major fires.[3] There are also several thousand gallons of highly combustible jet fuel in the wing storage tanks.

Despite aviation's admirable safety record, accidents do occur. During the eighteen-year period from 1965-1982, there were 2642 fatalities throughout the world in turbo-powered passenger aircraft

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accidents involving fire. These accidents involved in-flight fires or impact-survivable crashes followed by fire. Of these 2642 fatalities, approximately 2150 were attributable to the effects of fire.[4] A sumary of United States airline incidents involving smoke or fumes is presented in Table 1. It is now recognized that the cause of death in most fires, whether in residences, commercial buildings or aircraft accidents is not direct burns, hyperthermia or shock, but inhalation of toxic fire gases[5]. For a comprehensive analysis of aircraft fire and fatality statistics, the interested reader is referred to Hall and Stiefel's study[4].

1.3.1 The Fire Environment

Fire is an extremely hostile environment. Human tolerance to the products of combustion including visible smoke, fire gases, flame and heat, is very low. The key to survival from a fire is escape. If one has sufficient escape time, is conscious and mobile, and there are no physical obstacles (physical handicaps, locked doors, unsuitable egress areas, etc.), escape should be possible.[6] However, fire poses a combination of time-varying threats to life and safety which are due to the variety of physiological and behavioural effects resulting from the inhalation of fire gases and heated air. These contribute to obscuration of vision, physical incapacitation, loss of motor coordination, disorientation and panic. Delay of escape from fires can lead to subsequent injury or death due to inhalation of toxic gases and/or thermal burns. In addition, fire survivors may experience post-exposure respiratory disorders and thermal injuries leading to death.[6]

Clearly, fire poses an even greater risk to those with pre-existing functional impairment. These include the very old, the elderly, the physically handicapped, those with heart disease and those under the

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TABLE 1

10-Year History of Incidents Involving Smoke or Fumes in the Cabin or Cockpit (U.S. Incidents Only)

Year	Emergency Landing Made	No Emergency Declared	Unknown Status	Total No. of Incidents
1974	9	2	7	18
1975	11	1	4	16
1976	14	1	7	22
1977	11	8	2	21
1978	13	2	2	17
1979	19	3	2	24
1980	17	4	0	21
1981	9	7	1	17
1982	10	5	5	20
1983	17	9	4	30
Total:	130	42	34	206

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influence of alcohol, drugs or medication. One study has demonstrated that 66% of fire deaths were comprised of people under the age of nine or over sixty.[6]

1.3.2 Toxicity of Fire Gases

The fire environment contains a great variety of toxic gases. Well over 100 chemical species have been identified from the burning of some materials.[5] Therefore, assessment of the toxicity of smoke is far more complex than that involving a single chemical exposure. The complexity is increased when one considers the likelihood of interaction between toxics, including additivity, synergism and antagonism. Table 2 summarizes the toxic effects of common fire gases and describes their sources. Fire gases may be classified as systemic or irritant gases.

Systemic gases are a relatively small group and exert their toxic effect by interfering with vital biochemical processes which results in incapacitation or death. Descriptions of the two major fire related systemic gases, carbon monoxide and hydrogen cyanide, are presented below.

Carbon monoxide (CO) is the result of incomplete oxidation during a fire due to limited or inadequate oxygen in the combustion zone. This is usually the case except for premixed fuel and air. Therefore, CO is produced in essentially all fires.

Numerous studies have confirmed that CO is the major toxic in human fire fatalities.[5] Fire atmospheres frequently contain dangerous CO levels of several thousand parts per million (ppm).[6,8] Even considerably lower CO levels may be detrimental to fire survival. A number of studies, summarized in reference 6, have shown that relatively low carboxyhemoglobin levels in the blood can result in impaired

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TABLE 2

Toxicological Effects of Fire Gases[3,6]

Toxicant	Sources	Toxicological Effects	Estimated K_i Values (ppm-minutes)
Carbon Monoxide (CO)	product of incomplete combustion of materials containing carbon, present in essentially all fires	a rapidly fatal asphyxiant	34,250
Hydrogen Cyanide (HCN)	from combustion of wool, silk, polyacrylonitrile, nylon, polyurethane and paper	a rapidly fatal asphyxiant poison	1,200
Nitrogen Dioxide (NO_2) and other oxides of nitrogen	produced in small quantities from fabrics and in larger quantities from cellulose nitrate and celluloid	strong pulmonary irritant capable of causing immediate death as well as delayed injury	>2,000*
Ammonia (NH_3)	produced in combustion of wool, silk, nylon and melamine, concentrations generally low in ordinary building fires	pungent, unbearable odour; irritant to eyes and nose	>10,000*
Hydrogen Chloride (HCl)	from combustion of polyvinyl chloride (PVC), and some fire-retardant treated materials	respiratory irritant, potential toxicity of HCl coated on particulate may be greater than that for an equivalent amount of gaseous HCl	>86,450 (if particulate absent)

Note: The incapacitation dose constant, K_i, is defined as the product of toxicant concentration and exposure duration that will produce incapacitation.

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TABLE 2 (cont'd)

Toxicological Effects of Fire Gases[3,6]

Toxicant	Sources	Toxicological Effects		Estimated K_i Values (ppm minutes)
Carbon Dioxide (CO_2)	product of complete combustion of materials containing carbon, present at elevated levels in all fires	fatigue, dizziness, shortness of breath, hyperventilation		750,000
Other Halogen acid gases (HF and HBr)	from combustion of fluorinated resins or films and some fire-retardant materials containing bromine	respiratory irritants.	HF HBr	4,000* 5,000*
Sulfur Dioxide (SO_2)	from materials containing sulfur	a strong irritant, intolerable well below lethal concentrations		5,000*
Isocyanates	from urethane polymers, pyrolysis products such as toluene -2, 4-diisocyanate (TDI), have been reported in small-scale laboratory studies; their significance in actual fires is undefined	potent respiratory irritants; believed the major irritants in smoke of isocyanate-based urethanes		1,000 (TDI)
Acrolein	from pyrolysis of polyolefins and cellulosics at lower temperatures (400°C)	potent respiratory irritant		13,900

* Note: The results of the SWRI study on incapacitation doses of irritant gases may cast some doubt on these estimates.[6] In addition, the K_i values given for HCl and acrolein involved post-exposure fatalities.

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cardiovascular function, and reduced vigilance ability, reaction time, time discrimination and perhaps mental functions. All of these effects may be important to escape from a fire.

Hydrogen cyanide (HCN) is produced by combustion of materials containing nitrogen. These include silk, wool, nylon and polyurethane. The role of HCN in human fire fatalities is less clear than that of CO. In one study, HCN was detected at low levels in half of 90 sample runs during structural fires.[9] However, since elevated blood HCN levels are usually associated with high carboxyhemoglobin blood levels, the contribution of HCN alone to death often cannot be determined accurately.

Sensory and pulmonary irritant gases found in fires include halogen acids such as hydrogen fluoride, hydrogen chloride and hydrogen bromide (HF, HCl and HBr, respectively), aldehydes such as acrolein and a variety of others including oxides of nitrogen (NO_x), sulfur dioxide (SO_2), isocyanates and ammonia (NH_3).

Carbon dioxide (CO_2) is also produced by complete combustion of carbonaceous materials and is found at elevated levels in essentially all fires. CO_2 is not particularly toxic at levels normally found in fires but these moderate levels stimulate the rate of breathing. This condition can contribute to the overall hazard by causing accelerated uptake of other fire gases.[6]

Oxygen is consumed during a fire. When oxygen drops from its normal level of 21% in air to roughly 17%, motor coordination is impaired; when it drops to the range of 14% to 10% a person quickly becomes fatigued; in the range of 10% to 6% a person loses consciousness. Symptoms of oxygen deficiency may appear at higher levels if a person is under exertion.[6]

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Oxygen depletion is relatively rare in building fires[8,9] and airplane fires.[10,11] Full scale cabin fire testing at FAA[10,11,12] indicates that oxygen depletion does not occur until the flash-over condition when survival becomes problematical due to the rapid rise in temperature.

Over 80% of all fire fatalities are the direct result of inhalation of toxic gases (i.e., smoke) and not thermal injury.[13] Most fire victims suffer burns only after they have been incapacitated or killed by toxic gases. Some victims suffer no burn injuries at all; once they have received an incapacitating dose of smoke they collapse but continue to breathe until they have received a fatal dose. Thus, the toxicological endpoint of greatest relevance to fire safety is physical incapacitation (loss of one's ability to escape the fire environment). Accordingly, the important fire gas toxicity indices are time-to-incapacitation, T_i (minutes) and incapacitation dose constant, K_i (ppm-minutes).[14]

Incapacitating dose information is relatively scarce. Most toxicology studies focus on lethality as the key endpoint. As a result combustion toxicologists have had to rely on extrapolation from lethality endpoints and 8-hour threshold limit values. Recent studies have shown that such extrapolations can underestimate T_i values by orders of magnitude. For example, recent experimental work at Southwest Research Institute in San Antonia, Texas has provided data concerning K_i values for CO, HCl and acrolein.[3] The test species were the rat and juvenile African savannah baboon. The African savannah baboon is considered to be an acceptable primate surrogate for humans. Values determined for the primates are as follows:

Toxic	K_i (ppm minutes)
CO	34,250
Acrolein	> 13,900
HCl	> 86,450

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Prior to this study, the best data available for these gases was as follows:[11,14]

Toxic	Derived Incapacitation Dose K_i (ppm-minutes)
CO	24,000
Acrolein	1-300
HCl	2,400

As can be seen, the human K_i values determined by primate experiments for acrolein and HCl are 50 to 100 times greater than those derived by extrapolation. Another important finding of this study was that the rat appears to be a satisfactory surrogate for humans for both CO and irritant gas studies.

In order to assess the relative importance of each toxic in cabin fires, Dr. Crane of the Civil Aeromedical Institute (CAMI) has proposed a hypothetical human survival model.[11] The model allows estimation of time-to-incapacitation in a fire environment composed of a number of toxic gases and elevated temperature each varying with time.

The model has proved useful in evaluating the effect of fire-blocking seat cushions on time-to-incapacitation, T_i, during post-crash fires.[10,11,12] It can also be used to assess the effect of a given smoke mask on T_i. One need only add the protection factor term (P_i) to the fractional equivalent dose, FED_i, relation[14]. P_i is the ratio of the concentration of gas species "i" in the passengers breathing zone to the concentration in the cabin. The protection factor depends on the edge leakage and/or toxic gas filtration efficiency of each smoke mask.

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1.3.3 Passenger Cabin Safety

The concept of providing respiratory protection to airline passengers to allow escape from burning aircraft is not new. The idea was studied as early as 1967.[15] In 1969, in fact, the U.S. Federal Aviation Administration (FAA) issued Notice of Proposed Rule Making (NPRM) 69-211 which proposed the use of smoke hoods to provide airline passengers with respiratory protection in the case of fire. However, the notice was withdrawn on the grounds that use of smoke hoods could delay emergency evacuation.[16] Recent tragedies, however, such as the Cincinatti DC-9 fire in June, 1983 in which 23 of 46 passengers were killed has refocussed public attention on the issue of passenger cabin safety in general and passenger respiratory protection in particular.[17,18]

In 1980 the Special Aviation Fire and Explosion Reduction Advisory Committee (SAFER) completed their report on passenger cabin fire safety.[19] The SAFER committee made some 23 recommendations for upgrading airplane fireworthiness, including the following (in order of priority):

Post Crash Fire Hazards

- investigate and validate anti-misting kerosene (AMK)
- amend current regulations to require fuel tank vent protection during ground fires
- expedite FAA/NASA research to establish realistic airplane crash scenarios

Cabin Interior Material

- establish the contribution of cabin interior materials to the post-crash fire hazard

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- develop fire blocking layers for polyurethane foam cushioning material
- define post-crash fire scenarios and establish their applicability to fire modelling, research and design

Other Areas of Concern

- evaluate smoke masks and protective clothing for crew members to aid in post-crash emergency evacuation.

Many of the recommendations of the SAFER committee have already been acted upon by FAA. For example, an extensive laboratory test program on AMK was followed by a controlled impact demonstration (CID). The FAA Technical Centre has also developed a full-scale testing facility to simulate passenger cabin fires for study and has extensively studied the effect of fire-blocking seat cushions against cabin fires.[10,11,12]

In a recent staff study, FAA concluded that it was prudent to evaluate the practicality of providing passengers as well as crew members with emergency respiratory protection. Furthermore, they proposed that promising devices developed by industry should be evaluated by FAA and that if the evaluation proved positive, FAA should develop criteria for Technical Standard Order (TSO) approval.[20]

Current passenger oxygen systems are designed to protect passengers in case of decompression. They are designed to provide continuous flow and utilize high pressure gaseous oxygen.

A typical oxygen distribution system consists of manifolded (approx. 1800 psi) oxygen cylinders, delivering oxygen to a pressure reducer, and a variable pressure regulator controlled by an anaeroid valve sensitive to altitude.[21]

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The barometric controller incorporates an anaeroid triggering mechanism that automatically drops the mask. At the same time, oxygen is distributed into the lines and through calibrated flow orifices. As the altitude increases, the barometric controller increases pressure in the lines and hence produces a flow increase to the passenger mask. Oxygen flows to the passenger mask thus vary with the cabin altitude and are generally between 0 and 4.2 litres per minute (l/min), Normal Temperature Pressure Dry (NTPD).[21] There is a total supply of approximately 24 litres of oxygen (NTPD) per passenger[22]. Some of the newer generation of aircraft such as the L-1011 utilize chemical oxygen generating systems in the form of sodium chlorate candles. These systems provide roughly the same flowrates as gaseous oxygen systems.

It is important to understand that only when cabin altitude is roughly 40,000 ft. that the system provides oxygen flow equal to passenger minute volumes, i.e. the volume of air required in one minute for respiration. At altitudes below 10,000 ft. the oxygen flow is zero and passengers must derive their minute volumes from the cabin. At 33,000 to 34,000 ft. the added oxygen constitutes only one-half of the required 30 l/min minute volume. Again, the remaining 50% of the minute volume must be derived from the cabin.[23] Because of this use of cabin air, the current passenger oxygen systems are of limited value as smoke protection in an in-flight fire. As the aircraft descends, passengers would inhale more and more contaminated cabin air.

1.3.4 Passenger Aircraft Fires

Passenger aircraft fires involving risk to life can be classified as either post-crash or in-flight fires. Post-crash fires generally develop as a result of ignition of jet fuel released from storage tanks damaged by the crash. They are characterized by high

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radiant heat loads, some damage to the fuselage and relatively short periods of time to the flash-over condition. Flash-over involves the rapid growth of the fire from an area in the immediate vicinity of the fuel fire to the remaining cabin interior. It is not considered realistic to provide survival beyond the flash-over point.

The key to survival in post-crash fires is immediate evacuation of the cabin, and FAA[16] points out, that anything delaying evacuation (such as the need to don a smoke mask) is detrimental to survival. However, this does not preclude the use of smoke masks that can be donned while heading for the exits. McFadden, et al demonstrated in 1970 that such smoke masks, available at that time, did not, in fact, delay escape.[21]

In-flight fires usually occur in accessible areas such as galleys and are detected and extinguished promptly. On rare occasions they may also occur in inaccessible areas such as the baggage compartment. Such fires are characterized by low heat loads and a relatively long period of time to flash-over.

The key to survival in an in-flight fire is immediate landing of the aircraft and evacuation. The time required to make an emergency landing depends on the close proximity of an acceptable landing area and is in the order of 15 minutes over continental North America. In the Cincinatti accident, approximately 20 minutes elapsed between the discovery of the fire and landing of the aircraft.[24] Of paramount importance, therefore, is the protection of the respiratory system and maintenance of occupants in a conscious and mobile state so that they are able to evacuate.

Inaccessible in-flight fires are less common than post-crash fires. Of the 41 turbo-powered passenger aircraft accidents involving

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fire fatalities occurring world-wide in the period 1965 to 1982, only 7 or 17% involved in-flight fires. However, these 7 incidents resulted in 793 deaths or 37% of all fire fatalities, both in-flight and post-crash.

In general, human behaviour in fires is unpredictable. People can react calmly and rationally in a fire or they can give way to outright panic. They can even display "negative panic", which may be defined as an astonishing lack of awareness or disregard of the danger of fire.[13] In his review of actual occurrences from the files of the fire protection service, Strother-Smith made a number of observations concerning human behaviour in fires.[13] Some of these are as follows:

- The degree of threat experienced by the individual varies directly with the intensity of smoke, heat, noise and smell. It is at this point that healthy awareness of danger can give way to fear and panic.

- In general, people are not prepared to go through smoke even for short distances.

- Panic ensues when avenues of escape become evident. The survival instinct then overtakes rationality and escape routes are likely to become blocked.

- Panic response to fires is more likely to occur in a group situation than on an individual basis.

- The outcome of these group situations is usually dependant on the logic and rationality of one or a few individuals.

- The threat of fire in familiar surroundings does not appear as great as that in unfamiliar surroundings.

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Snow et al[25] analysed human behaviour in three aircraft fires that could be graded as (a) mild, (b) intermediate, and (c) extreme, in terms of environmental lethality. They found that the degree of panic generally paralleled the environmental intensity. There were relatively few examples of outright panic, however. Passengers in these incidents appear to have acted relatively calmly and rationally compared with people in many building fire incidents.[26]

Barthelmess studied the Cincinatti accident from a human-factors perspective.[24] The following key question was asked: "Why did half the occupants on board perish while the other half did not?". She made a number of interesting observations and conclusions:

- Contrary to what is widely believed, survivors were not saved by breathing through wet towels. In fact, only a small percentage of passengers who were given wet towels survived.

- Some survivors experienced significant eye irritation but none found it to be intolerable.

- There was little evidence of panic among the passengers.

- The cabin was "virtually black". It was impossible to see clearly.

- The single most important factor in surviving the accident appears to have been the extent to which the occupants took responsibility for their actions. The survivors had a "mental game plan" on when and how to escape the aircraft fire.

In summary, one is struck by the relative absence of outright panic among airline passengers. They appear to act relatively calmly and

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rationally compared to people in building fires. As Strother-Smith has noted, the outcome of these group situations usually depends on the logic and rationality of one or a few individuals. The presence of the flight crew may calm the group, making rational response more likely.

2. SMOKE MASK CRITERIA AND TEST PROTOCOLS

2.1 Current Standards

There are currently no standards for airline passenger smoke masks. The most thorough respirator standards in existence are those relating to the field of occupational health. Extensive industrial experience has led to a comprehensive understanding of respirator use. Good examples of occupational respirator standards are ANSI Z88.2-1980, ANSI Z88.6-1984 and CSA Z94.4-M1982.[27,28,29]

Industrial use, however, is wholly different from emergency escape use. Therefore, the above standards are not directly relevant to smoke masks. Industrial respirators are usually designed to protect the wearer from both the long-term and acute effects of a narrow range of contaminants. Users are trained in their use and operation and usually have a good idea of the nature of the hazard. They are rarely used in emergency situations. Because they are generally worn repeatedly, wearers can become familiar with the operation of their respirators. By contrast, smoke masks are designed for a one-time use by people unfamiliar with them and untrained in their use. They are designed to protect against incapacitation for a relatively short period of time in the unpredictable environment of a fire.

The British Standards Institute has circulated a draft emergency escape smoke mask specification for discussion.[1] It is quite broad in scope and specifies basic construction, materials, packaging and performance requirements for smoke masks utilizing filtration of contaminants from otherwise breathable air.

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The FAA issued in June 1983 Technical Standard Order C99 entitled "Protective Breathing Equipment.[2] This document provides specifications for flight crew emergency respirators including components, materials and performance requirements. It also specifies that flight crew protective breathing equipment must be self-contained breathing apparatus.

2.2 Purpose of Airline Passenger Smoke Masks

The purpose of emergency smoke masks is to protect people against incapacitation from inhalation of toxics for short periods in order to permit evacuation from the hazardous fire environment.

It is also desireable that an airline passenger smoke mask have the following characteristics:

- light and compact for easy storage,
- easy to don quickly by passengers unfamiliar with the device,
- capable of protecting the wearer from the wide variety of toxicants that might be present in a cabin fire for periods of approximately 20 minutes or more based on in-flight landing capability,
- allows mobility of wearer,
- vision and vocal communication is possible,
- provides acceptable breathing air quality,
- inexpensive,

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- long storage life,
- able to fit a wide variety of faces including those of both men and women, children and senior citizens,
- able to provide protection in both in-flight and post-crash fire scenarios, and
- totally self-contained and not dependant upon external sources of oxygen.

2.3 Criteria

In order to evaluate the performance of each candidate device, the following criteria were selected.

2.3.1 Edge Leakage

Edge leakage refers to the penetration of contaminants through the seal of the smoke mask. This does not include leakage through a filtration cartridge. Extensive industrial experience has shown that leakage due to improper fit or seal largely determines how effective the respirator will be. Testing procedures have been devised to measure leakage. Results of such tests are given as percent leakage or as a protection factor which is simply the reciprocal of percent leakage.[27,29]

In general, measurement of edge leakage involves exposing the smoke mask wearer to a test atmosphere containing an easily detectable non-toxic aerosol vapour or gas as the test agent and measuring the penetration of the test agent into the smoke mask. While wearing the

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smoke mask, the wearer performs a series of tasks simulating typical activities. The smoke mask is fitted with sampling probes that are connected by means of flexible tubing to an instrument that measures penetration of the test agent into the respirator.

The British Standards Institute has proposed the following standards for edge leakage of emergency escape smoke masks utilizing filtration of otherwise breathable air.[1]

a) not more than 2% in the breathing zone

b) not more than 10% in the ocular zone

The TSO-C99 draft for flight crew protective breathing equipment[2] specifies edge leakage of not more than 5% in the breathing zone and not more than 10% in the ocular region.

2.3.2 Smoke and Toxic Gas Penetration (Filtration Systems)

Smoke masks which utilize filtration of inhaled air must be evaluated to determine the smoke and toxic gas removal capability of the filtration system. BSI has proposed that when tested at flowrates of 30 l/min the penetration times of HCl, HCN, acrolein and CO shall not exceed the values outlined in Table 3. BSI also specifies that filter penetration by particulates shall not exceed 6%.[1]

2.3.3 Condition of Inhaled Air

The term "condition of inhaled air" refers to the levels of oxygen, carbon dioxide and temperature in the breathing zone of each smoke mask. These indices are directly related to comfort.

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TABLE 3

Test Gases and Minimum Penetration Times
for Filtration Devices

Test Gas	Breakthrough Value (ppm)	Test Concentration (ppm)	Minimum Penetration Time (minutes)
HCl	5	1000	10
HCN	10	200	10
Acrolein	0.3	20	10
CO	500	10,000	10

Source: BSI Draft Spec.
Sections D.3 and D.4

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Air temperatures in the breathing zone of a smoke mask are unlikely to approach levels required to produce physical injury. However, they do have an obvious effect on comfort. Clearly the hotter the wearer feels, the more likely they are to remove the device if they panic.

The BSI draft standard[1] for smoke masks specifies the following:

a) CO_2 levels in the breathing zone shall not exceed 3%

b) inhaled air temperatures shall not exceed $50^{o}C$ (wet-bulb) or $90^{o}C$ (dry-bulb)

BSI does not specify a minimum level for oxygen in the breathing zone.

2.3.4 Ease of Donning

It is important that successful donning of the smoke masks can be done by untrained people. Based on brief instructions, the smoke mask should be donned easily, in a minimal time period and once on, the fit or seal should be sufficient to provide proper protection.

Ease of donning can be evaluated by giving brief donning instructions, similar in length and degree of detail to those likley to be given by a flight attendant in a pre-flight demonstration. After instruction, the subjects are asked to don the mask. After donning, the subjects and supervising scientist complete a questionnaire to document the subjects' subjective response and ergonomic factors affecting ease of donning.

The BSI draft standard does not include a specification for ease of donning. The TSO-C99 standard for flight crew protective breathing equipment specifies a maximum donning time of 15 seconds.

2.3.5 Vision and Vocal Communications

It is important that the smoke mask not impair vision and communication which are necessary for rapid evacuation from a passenger cabin fire. The BSI draft has two simple tests to assess this aspect. They are presented in Section 2.4.5.

2.3.6 Breathing Resistance

Smoke masks which utilize filtration must be evaluated to determine inhalation and exhalation resistance. Excessive resistance will adversely affect the ability to inhale clean filtered air and exhale stale air. In order to determine resistance, air is drawn through the filters and the pressure drop measured. The BSI draft standard[1] specifies that breathing resistance shall not exceed 8 mbar inhalation and 3 mbar exhalation at a flowrate of 30 l/min.

2.3.7 Resistance to Flame

Flammability standards generally consider ignition times of 3 to 5 seconds as satisfactory.[26] The BSI draft standard specifies that smoke masks shall not grossly soften, deform, or decompose and shall not continue to burn after exposure to propane burners.[1]

TSO-C99 specifies that the protective breathing equipment meet Federal Aviation Regulation 25.853 and Underwriters Laboratory Test 94. These standards entail testing of all the materials making up a given

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smoke mask in terms of average burn length, degree of self-extinguishment of drippings, average flame time after removal of flame, average glow time, etc. The standards are designed for testing passenger cabin materials.

2.3.8 Weight, Size and Cost Considerations

It is important that smoke masks be light, compact and relatively inexpensive. The passenger cabin has very limited storage space. Smoke masks for up to 300 passengers would be difficult to store if they are at all bulky.

Smoke mask costs that could be considered include the following:

- capital cost,
- installation costs,
- servicing, inspection, testing and maintenance costs, and
- repair and replacement costs.

This criteria assesses the practicality of using a smoke mask for passenger airline use, not its ability to protect a passenger from fire gases and, consequently, was not considered further.

2.4 Test Protocols

2.4.1 Edge Leakage

Test Chamber

A schematic of the tracer test chamber and associated equipment is presented in Figure 1.

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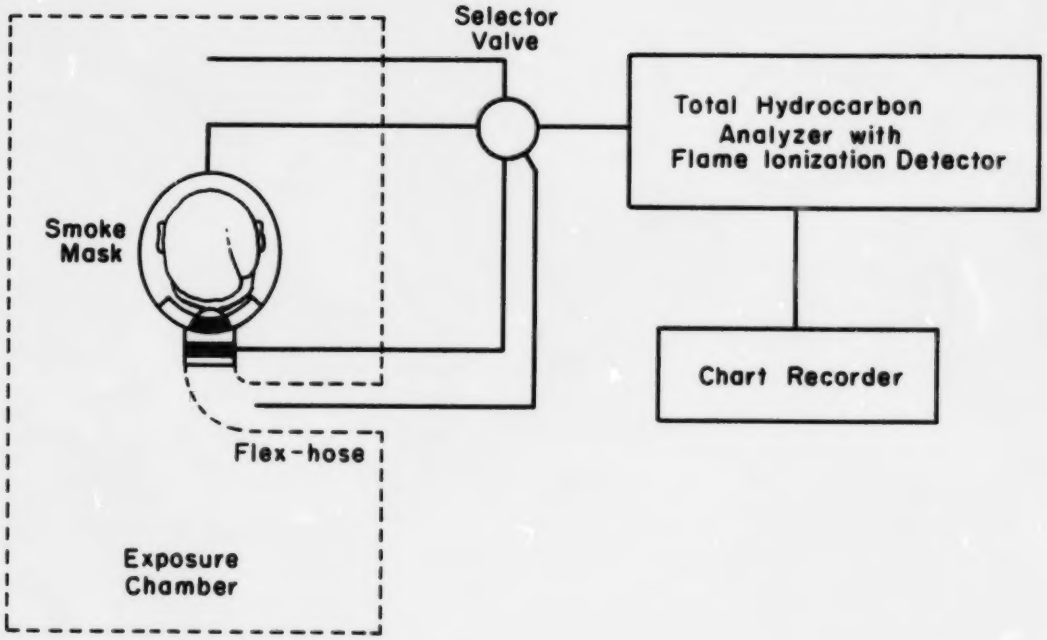

FIGURE 1: METHOD FOR EDGE LEAKAGE MEASUREMENT.

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An exposure chamber with a volume of 3 cubic meters was fabricated of cedar, plywood and plexiglass. The chamber was capable of containing one subject with sufficient room to perform the required activities. To allow observation of the subject, large plexiglass panels were incorporated into all four chamber walls. A large, easy-to-open door provided quick access to the subject. There was a small blower in the chamber to ensure a uniform mixture of test gas and air. The chamber is displayed in Photographs 1, 2 and 3. Small sampling ports were inserted into the breathing (mouth) and ocular (hood) zones of each smoke mask to provide for tracer gas collection. Small-bore flexible tubing was passed through the exposure chamber wall and connected the sampling ports to a selector valve located outside the chamber. Smoke mask filter units were isolated from the chamber by means of a flexible hose. The sample gas was drawn at a rate of 1 l/min and analysed by a Ratfisch IPM Total Hydrocarbon Analyzer RS5 Flame Ionisation Detector. A major advantage of the method is that it involves <u>real time</u> analysis of leakage.

Edge leakage was calculated by determining the ratio of the test gas level inside the smoke mask to that in the exposure chamber for each exercise activity. The average of all these ratios was calculated to give the average edge leakage value for that mask and subject.

Propane (C_3H_8) was selected as the test gas for the the edge leakage tests. This selection was based on the following considerations:

i) propane is a light volatile gas which equilibrates rapidly and does not condense in sample lines,

ii) propane has a molecular weight of 44 and is in the range of many known products of aircraft fires (see Table 4),

iii) propane is a relatively benign gas and is not toxic at the concentrations used (approximately 300 ppm),

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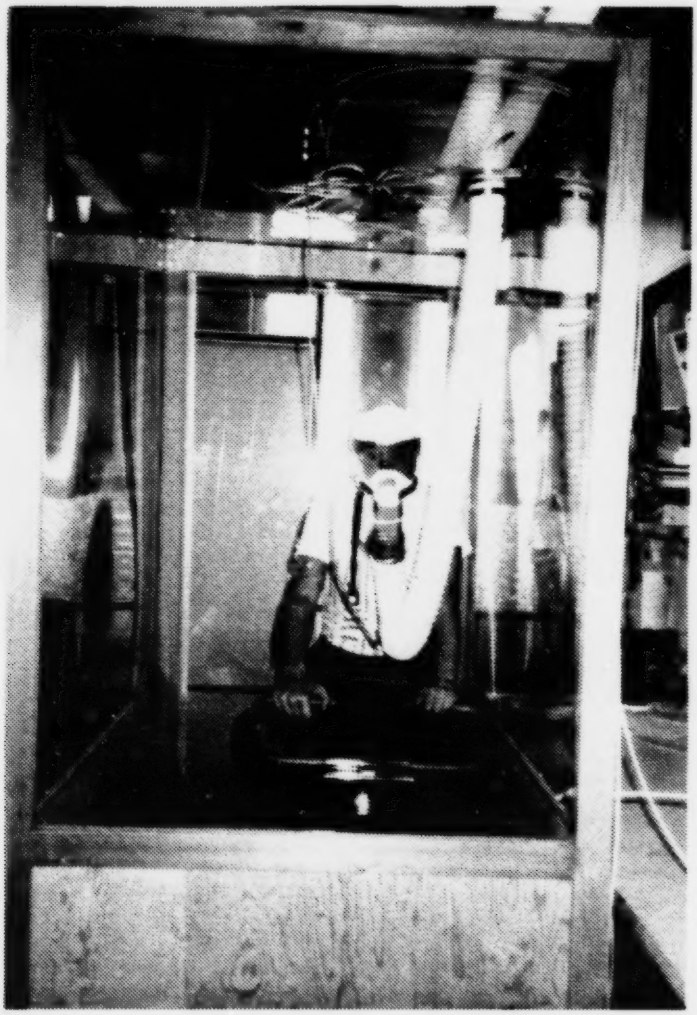
PHOTOGRAPH 1

Edge Leakage Test Chamber



Note: The flexible hose is used to isolate the filter unit from the test atmosphere. The subject is exercising on a bicycle ergometer.

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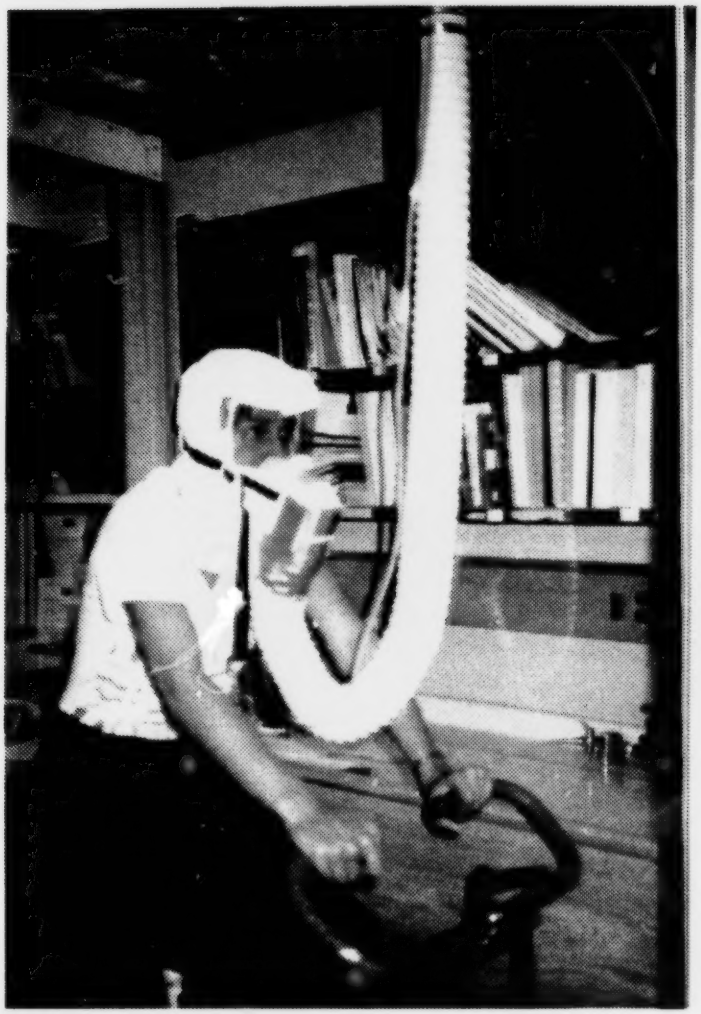
PHOTOGRAPH 2

Edge Leakage Test Chamber



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PHOTOGRAPH 3

View of Inside of Edge Leakage Test Chamber

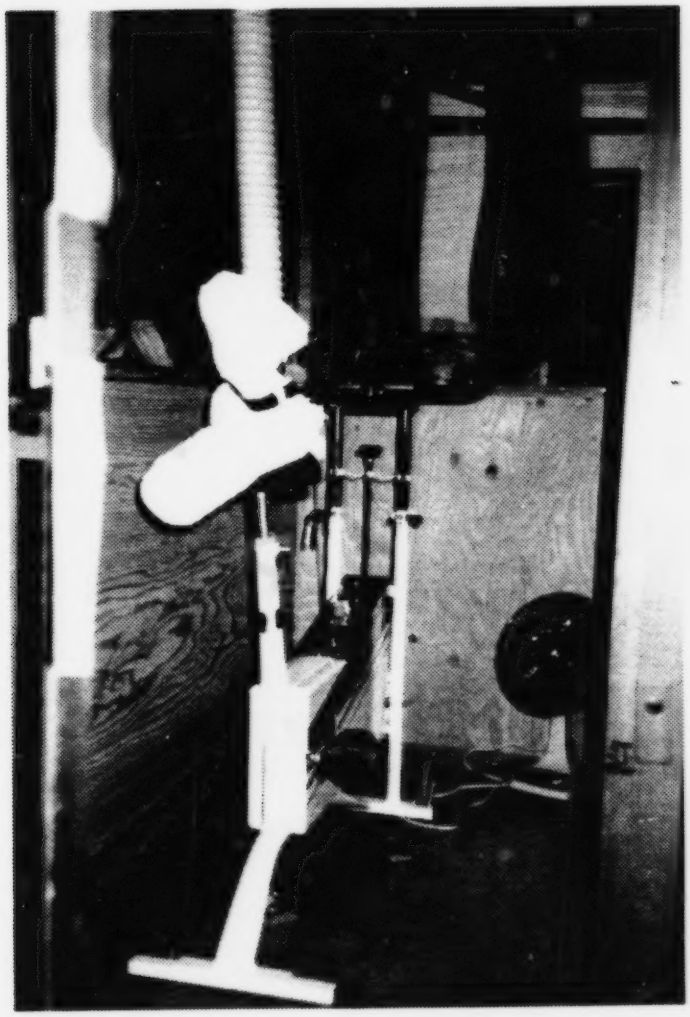

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TABLE 4

Comparison of Molecular Weights
of Common Combustion Products
Produced in Aircraft Fires

Combustion Product	Molecular Weight
Hydrogen Fluoride	20
Hydrogen Cyanide	27
Carbon Monoxide	28
Hydrogen Chloride	36
Acrolein	56

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iv) propane is non-irritating to the test subject,

v) propane does not require specific handling procedures or work areas as would be required by irritating test gases, and

vi) very small amounts of propane can be measured in real time with little difficulty.

Isopropyl alcohol (IPA) was also used as a trace gas to corroborate the results obtained with propane and because one of the candidate smoke masks (Vivat hood) utilizes a filter that could not be effectively isolated from the test chamber. For all other smoke masks utilizing filtration, it was easy to isolate the filter unit by connecting it to a flexible hose. See Photographs 1 and 2 and Figure 1. To ensure that filters were effectively isolated from the chamber, propane levels were periodically measured in the flexible hose and were found to be zero.

Isolating the filters in this manner is an improvement over current test practices. Currently, filters are isolated by means of high efficiency filters, but this can effect the pressure differential across the mask filtration unit and thus influence the leakage results.

Test Subjects

Ten subjects per smoke mask, 5 males and 5 females, were tested for edge leakage. They were drawn from a pool of 17 volunteers, all of whom are employees of Ontario Research Foundation. The pool of volunteers was selected to include male and female subjects with different facial features and body sizes as would be expected of airline passengers. Four of the subjects wore glasses and one had a beard. The test subjects are characterized in Appendix A.

Smoke Mask Donning Instructions

The supervising scientist gave each subject donning instructions similar in length and detail to those that would be given by flight attendants in a pre-flight demonstration. The supervising scientist did not attempt to ensure optimal fit. Subjects were given a general overview of the tests but had not seen the smoke masks prior to testing.

Exercise Activities of Test Subjects

The test subjects performed the following series of activities while in the test chamber:

(a) normal breathing,

(b) talking,

(c) moving head up and down and from side-to-side, and

(d) exercising at a 50-watt workload as measured on a Monark bicycle ergometer.

Each activity was performed for a period of two minutes.

2.4.2 Smoke and Toxic Gas Penetration

Smoke and toxic gas penetration test protocols were not developed. The evaluation was based on comparing manufacturer test data to the BSI draft standard criteria.

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2.4.3 Condition of Inhaled Air

Five (5) subjects per smoke mask were tested for condition of inhaled air. They were drawn from a pool of 17 volunteers and are characterized in Appendix A.

Subjects were tested while resting and while exercising at a 50 watt workload, as measured on a bicycle ergometer. The latter test was adopted to impose a moderate metabolic load on the subject as might be expected in an passenger cabin emergency. Each subject was tested for at least 10 minutes at rest and 10 minutes at the 50 watt workload.

Figure 2 is a schematic of the equipment used to assess the condition of inhaled air. Each mask was fitted with a sufficient number of sampling ports to measure each parameter. Test gas was sampled at flowrates of 1 Lpm. Since the methods of analysis did not involve altering the test gas in any way, test gas samples were continuously recirculated to the smoke mask.

Carbon dioxide levels were measured using a Horiba A1A23 Non-dispersive Infrared Analyser. Oxygen levels were measured using a Taylor Servomex OA 272 paramagnetic analyser. These are both real-time monitors. Temperature levels were measured using a K-type thermocouple wire connected to an Omega 881F Digital Multimeter. Results of all measurements were recorded on a multi-pen recorder.

2.4.4 Ease of Donning

Ten subjects, 5 male and 5 female, were tested for ease of donning in conjunction with the edge leakage tests.

Different questionnaires developed for each smoke mask type, Figure 3, were used in evaluating ease of donning.

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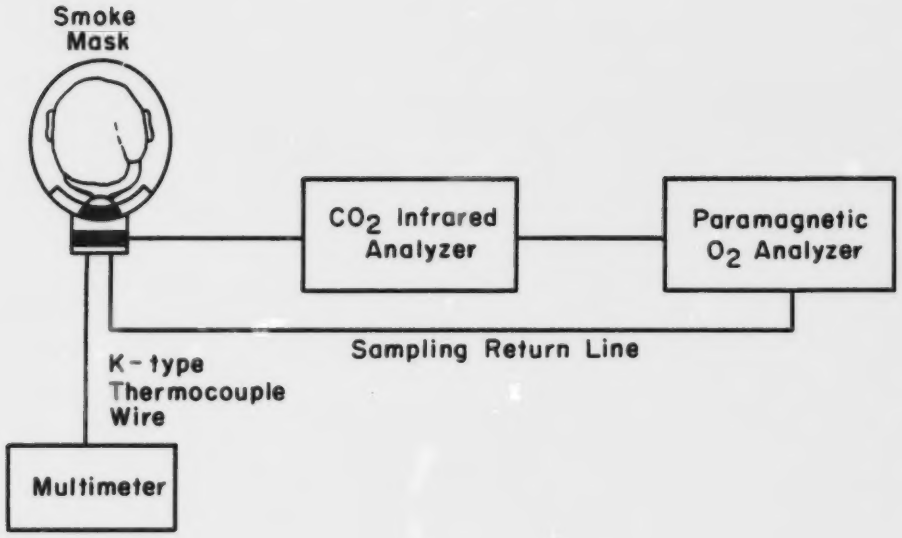

FIGURE 2: METHOD FOR MEASUREMENT OF CO_2, O_2 AND TEMPERATURE.

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Figure 3

Ease of Donning Questionnaire - Example

HOOD: Parat, Safeaire, Auer S-cape

Subject Identification: _____

Age (Approx): _____

M _____ F _____

Glasses: Yes _____ No _____

1. Please indicate the amount and nature of difficulty you experienced with each of the operations listed below.

Operation	Amount of Difficulty none 0	some 1	a lot 2	Nature of Difficulty
Donning Hood				
a) loosening strap	_____			
b) unfolding hood	_____			
c) spreading neck seal	_____			
d) pulling over head	_____			
e) positioning hood	_____			
f) tightening straps	_____			
g) other	_____			(explain) _____
Total	_____			

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Figure 3 (cont'd)

Removing Hood

a) loosening straps _____
b) pulling off hood _____

Total _____

2. Please indicate the amount and nature of any difficulty you experienced in understanding and/or remembering instructions for the following operations:

Operation	Amount of Difficulty none 0	some 1	a lot 2	Nature of Difficulty
Donning Hood				
Removing Hood				

3. Below is a list of sensations and reactions that may or may not be associated with wearing a mask. Please use a number to indicate the extent to which you experienced each of these.

	none 0	some 1	a lot 2	Did the sensation persist? Yes/No
a) claustrophobia				
b) fear of air shortage				
c) panic				
d) loss of hearing ability				
e) disorientation				
f) unpleasant odour				
g) sense of poor fit				

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Figure 3 (cont'd)

h) skin irritation

i) other (explain)

4. The space below is for comments on any design or other features of the hood which may not be covered above.

_____

_____

_____

_____

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2.4.5 Vision and Vocal Communication

Vision: A person with normal vision wearing a smoke mask shall be able to read a red-lit "EXIT" sign with letters 100 mm high from a distance of 10 metres.

Vocal Communication: A person wearing a smoke mask shall be able to converse with a person not wearing a smoke mask and standing 2 metres away.

2.4.6 Breathing Resistance

Breathing resistance tests were conducted on smoke masks utilizing filtration. Flowrates of approximately 30 Lpm were drawn through the filters and the pressure drops measured.

2.4.7 Flame Resistance

Flame resistance protocol tests were not developed or conducted.

3. SELECTION OF CANDIDATE SMOKE MASKS

After a search of the emergency breathing protection equipment market and scientific and patent data bases, 24 potential smoke masks were identified. A variety of concepts were represented by these devices, including the following:

- simple hood with neck or waist seal and no oxygen supply,
- hood with portable oxygen supply,
- hood with hose for connection to aircraft oxygen system,
- hood with filtration unit,
- hood with mouthpiece and filtration unit,
- hood with facepiece and filtration unit,
- mouthpiece with filtration and goggles,
- facepiece with filtration and goggles, and
- current passenger oxygen mask with rebreather bag.

From the 24 devices, 6 were selected for inclusion in the test program. These were selected according to the following criteria:

- a variety of smoke mask concepts must be represented,
- candidate smoke masks must not be excessively bulky or expensive,
- previous testing of smoke mask performance has been favourable, and
- candidate smoke masks must be commercially available or imminently so.

Many of the masks identified were eliminated by the weight/bulk criterion. These were generally industrial respirators equipped with portable oxygen systems. One device was eliminated due to unfavourable

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previous testing.[26] A number were eliminated because they were not commercially available. Some were patents that have not been acted on, and others are still in the development stage.[27]

The following devices were selected for inclusion in the test program:

- Vivat Escape Mask
- PELS System
- Smokefighter
- Parat Mask
- S-cape Hood
- Safeaire Hood

These devices are briefly characterized in Table 5 and described in the following sections.

3.1 Vivat Escape Mask

The Vivat Escape Mask is a product of Cybertronics Ltd. of Berkshire, U.K. It is being marketed in the U.S. and Canada by Puritan Bennett Aero Systems Co. of Lenexa, Kansas. The Vivat consists of a lightweight hood with a rubber neck seal and a filtration "mask". The hood is made of kapton, a lightweight, non-flammable and durable material developed by Dupont. The "mask" consists of several layers of filtration material including carbon fibre felt and activated charcoal layers.

The Vivat weighs roughly 70 g and is very compact; when folded in its outer envelope it measures 18 cm long, 14 cm wide and 1 cm thick.

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TABLE 5

Candidate Smoke Masks

Mask	Manufacturer/ Distributor	Description	Approx. Weight (g)	Approx. Size of Package	Approx. Cost (Cdn. $)
Vivat Escape Mask	Cybertronics Ltd. Berkshire, U.K., Puritan Bennett Aerosystems Co. Lenexa, Kansas	kapton hood with rubber neck seal, filter unit; does not filter CO	70	L=18cm W=14cm H= 1cm Volume=252cm^3	55
PELS System	Xenex Corporation Kaneohe, Hawaii/ Dupont, Wilmington, Delaware	Teflon hood with silicone neck seal, bed of LiOH on inner surface for CO_2 absorption	250	L=20cm W=16cm H= 5cm Volume=1600cm^3	250-300
Smoke-fighter	Smokefighter Inc. Chicago, Illinois	mouthpiece with filter attached to goggles, exhalation valve does not filter CO	270	L=15cm W= 9cm H=10cm Volume=1350cm^3	60
Parat Mask	National Draeger Inc., Pittsburgh, Pa.	hood with visor and knit neck seal, rubber facepiece with filter, no exhalation valve; filters CO.	550	L=14cm W=14cm H=21cm Volume=4116cm^3	83
S-cape Hood	MSA Ltd. Pittsburgh, Pa.	hood with visor, no neck seal, rubber facepiece with filter, exhalation valve, filters CO	570	L=15cm W=12cm H=24cm Volume=4320cm^3	136

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TABLE 5 (cont'd)

Candidate Smoke Masks

Mask	Manufacturer/ Distributor	Description	Approx. Weight (g)	Approx. Size of Package	Approx. Cost (Cdn. $)
Safeaire Hood	Emex International Safety Corporation, Vancouver	hood with visor, no neck seal, rubber facepiece with filter, exhalation valve, filters CO	500	L=16cm W=10cm H=19cm Volume=3040cm^3	125

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Previous testing of the Vivat device commissioned by the manufacturer has included the following:[30]

- edge leakage,
- contaminant penetration of filter involving the following test gases: toluene, formaldehyde, chlorobenzene, styrene, HCl, isocyanates, including TDI and MDI, acrolein, phosgene, acetic acid and particulate,
- breathing resistance,
- CO_2 buildup, and
- flammability.

In general, the results of the tests were favourable although there was some concern regarding CO_2 buildup and fogging when the subject is under a metabolic load. Photograph 4 displays a subject wearing the Vivat hood.

3.2 PELS System

The PELS System is being developed by E.I. Dupont de Nemours & Co. in conjunction with the Xenex Corporation of Hawaii. The PELS System is in the prototype development stage. It is a modification of the original Schjeldahl hood tested by McFadden et al in 1970.[21] The PELS System consists of a large Teflon hood roughly 26 litres in volume with a silicon neck seal. The inside of the hood is partly covered with a bed of lithium hydroxide (LiOH) which absorbs CO_2. The PELS System tested is displayed in Photograph 5. The unit tested weighed approximately 250 g.

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PHOTOGRAPH 4

The Vivat Hood

Note: The hood in the photograph has been fitted with sampling ports to the left and right of the wearer's forehead.

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PHOTOGRAPH 5

The PELS System

Note: The hood is not fully inflated. The white corrugated material is the LiOH bed. A flexible hose was connected to the hood to provide oxygen. In practice this would not be required as the hood would have its own oxygen supply.

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Currently, the proposed principle of operation for the PELS System is that the smoke mask will be self-contained with its own light-weight oxygen source. When an emergency fire situation arises, the passengers will don the mask and activate the oxygen supply. The oxygen source will inflate the hood, at which point the source will be depleted. The passenger with the hood on will then be isolated from the toxic fire environment and the oxygen enriched atmosphere and CO_2 control system will provide suitable breathing air for greater than 30 minutes.

CO_2 buildup is the limiting factor with the PELS System. Preliminary testing by the manufacturer was witnessed ORF project members. The testing was conducted at normal temperature and pressure. The subject was a 42 year-old 200 pound male. The hood was given an oxygen flow of 15 l/min for 2 minutes and then 1 l/min for 13 minutes for a total of 43 litres of oxygen. Current oxygen systems can provide each passenger with roughly 24 litres (NTPD) of oxygen in total.[22]

Testing by the manufacturer was conducted with the subject at rest and under a moderate to heavy workload. Testing with the subject at rest gave a favourable result. CO_2 buildup was effectively controlled and the subject was able to wear the device for over forty minutes without excess discomfort. In the workload test, however, CO_2 levels rose rapidly and the subject had to discontinue the test after approximately 8 minutes due to severe discomfort.[31]

The manufacturer is currently experimenting with various LiOH configurations and quantities to control CO_2 buildup. Only 3 PELS System units were available for this testing program. The self-contained oxygen supply sources were not available on the PELS systems tested. In order to simulate an oxygen source, oxygen at 2 l/min was supplied to the hood for the first 12 minutes of testing.

3.3 Smokefighter

The Smokefighter is a product of Smokefighter Incorporated of Chicago. The device consists of a mouthpiece filtration unit connected to goggles. It weights approximately 270 g and is packaged in a zip-lock bag.

The Smokefighter filter unit consists of a particulate filter backed up by a bed of adsorbent. There is an exhalation valve. The manufacturer has performed the following tests on the device:[32]

- emergency escape in simulated fire situations,
- filtering efficiency for the following test materials: HCl, CO, total hydrocarbons and particulate, and
- breathing resistance.

The Smokefighter has performed well in simulated fire situations and has received praise from a number of fire departments.[32] The filtration unit effectively removes particulates, total hydrocarbon test gas and HCl. It does not filter out CO.

Photographs 6 and 7 display the Smokefighter.

3.4 Parat Mask

The Parat Mask is a product of Drager of W. Germany. It consists of a flame-retardant hood with a visor and a knit neck-seal and a facepiece filter. There is no exhalation value. It weighs 550 g. and is sealed in an aluminum cylinder.

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PHOTOGRAPH 6

The Smokefighter

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PHOTOGRAPH 7

Side View of the Smokefighter

Note: Sampling ports have been fitted to filter housing of this device.

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The National Institute of Occupational Safety and Health (NIOSH) has conducted the following tests on the Parat device:[26]

- edge leakage,
- filter leakage of particulates, HCl, CO, HCN, Cl_2, H_2S, SO_2, NH_3 and NO_x,
- breathing resistance, and
- flame resistance.

NIOSH concluded that the Parat offered some protection against particulates and protects against a select group of gases and vapours including CO.[26]

The Parat hood is displayed in Photographs 8 and 9.

3.5 S-cape Hood

The S-cape hood is a product of MSA Limited. It is similar to the Parat mask and consists of a fire-retarded hood with visor and a facepiece filter unit. Unlike the Parat it has an exhalation valve but no neck seal. It weighs approximately 570 g and is factory-sealed in foil. It is packaged in a box measuring 24 cm by 15 cm by 12 cm. MSA has conducted extensive testing on the S-cape hood, including the following:[33]

- edge leakage,
- filter penetration of particulates, CO, NH_3, HCl, HCN, SO_2, H_2S, Cl_2 and CCl_4,

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PHOTOGRAPH 8

The Parat Hood

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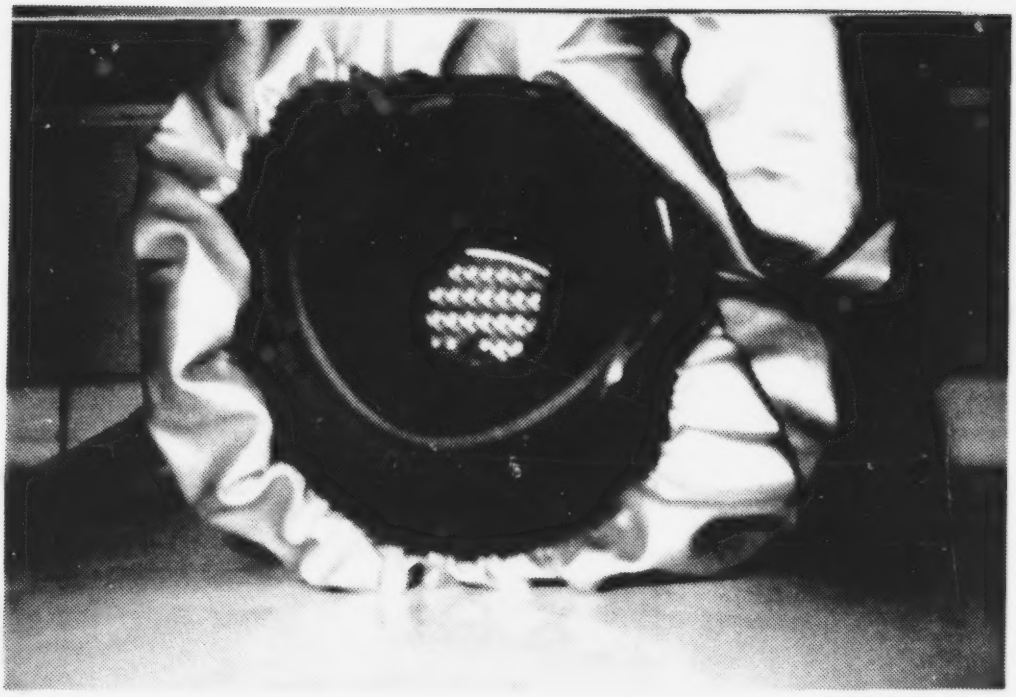
PHOTOGRAPH 9

Rear View of the Parat Facepiece



Note: The Parat Device does not have an exhalation valve. As can be seen, there is a knit neck seal.

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- breathing resistance,
- CO_2 content of inhaled air,
- vision and communication, and
- escape tests in simulated building fires.

The mask performed favourably in these tests. Photographs 10 and 11 display the S-cape hood.

3.6 Safeaire Hood

The Safeaire emergency smoke hood is a product of the International Safety Corporation of Vancouver. It is similar to the Parat and S-cape devices and consists of a hood with visor, and facepiece with filter. There is an exhalation value but no neck seal. The device weighs approximately 500 g and is factory-sealed in aluminum foil. It is sold in a box measuring roughly 19 cm by 10 cm by 16 cm. The manufacturer has conducted the following tests:[34]

- filter penetration of CO, H_2S, SO_2 and acrolein, and
- breathing resistance.

The Safeaire performed satisfactorily under these tests. Photograph 12 and 13 display the Safeaire device.

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PHOTOGRAPH 10

S-Cape Hood

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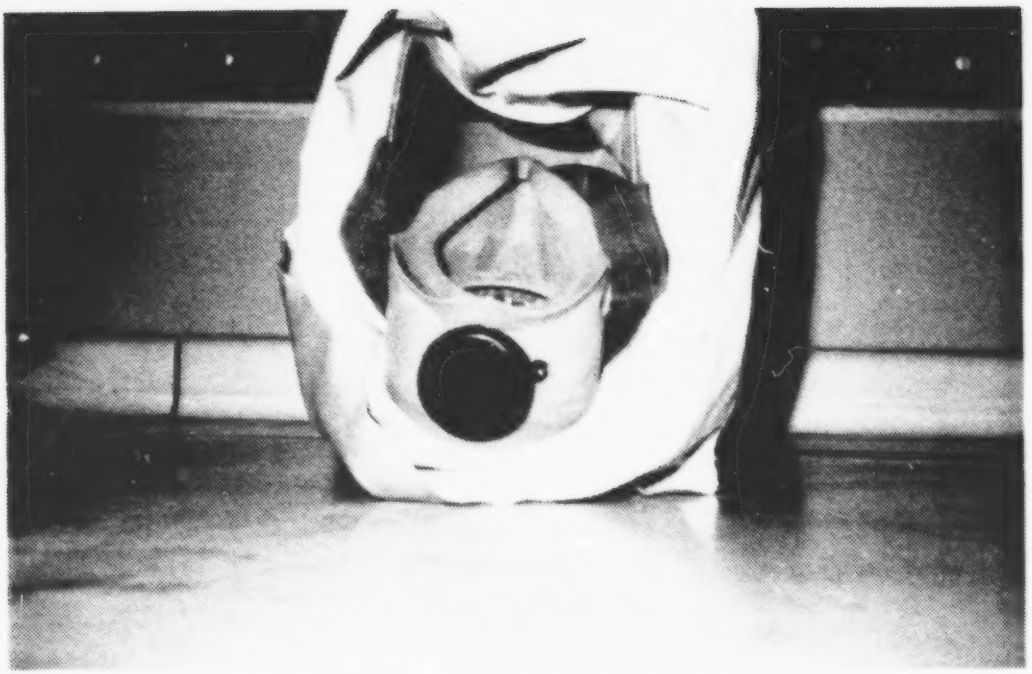
PHOTOGRAPH 11

Rear View of S-Cape Facepiece



Note: The black disc in the photograph is the exhalation valve. The S-cape does not have a neck seal.

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PHOTOGRAPH 12

The Safeaire Hood

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PHOTOGRAPH 13

Rear View of Safeaire

Note: This hood has been fitted with a sampling port in the breathing zone.

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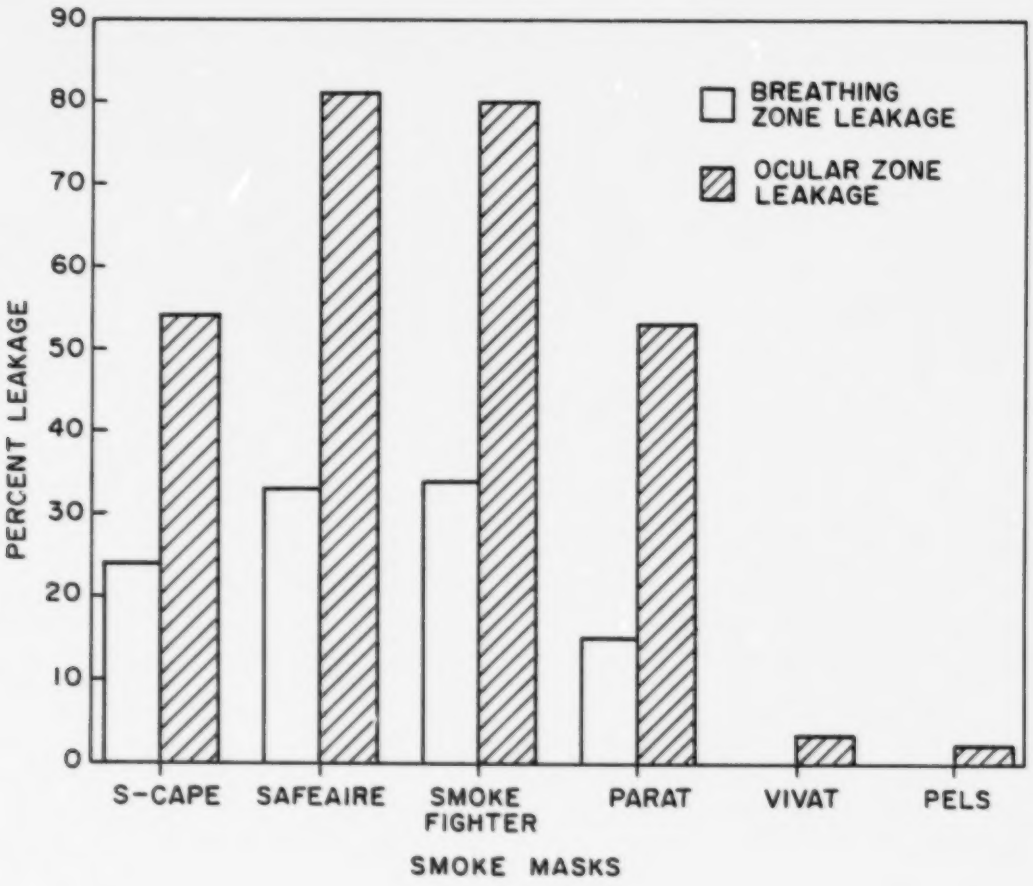
4. CANDIDATE SMOKE MASK TESTS

4.1 Edge Leakage

The edge leakage results are summarized in terms of bar graphs in Figures 4 to 6. Leakage results are given for both the mouth and hood areas for all smoke masks except the Vivat and the PELS System. For these latter two smoke masks, only hood leakage is given as this is representative of both the breathing and ocular (hood) zones. The tables summarize mouth and hood leakage for all subjects combined and for male and female subjects separately.

The following observations were made:

- the smoke masks with rubber or silicon neck seals (Vivat and PELS) have the lowest edge leakage (3% and 2%, respectively),
- hood leakage exceeds 50% for all other smoke masks,
- the average mouth leakage results for systems utilizing facepieces (Parat, S-cape and Safeaire) are 15, 24 and 33%, respectively, and
- the average mouth leakage for the smoke mask with the mouthpiece (Smokefighter) was 34%.



NOTE: FOR THE VIVAT AND PELS DEVICES, THE EDGE LEAKAGES INTO THE BREATHING AND OCULAR ZONES ARE EQUIVALENT.

FIGURE 4 : SMOKE MASK EDGE LEAKAGE RESULTS – ALL SUBJECTS

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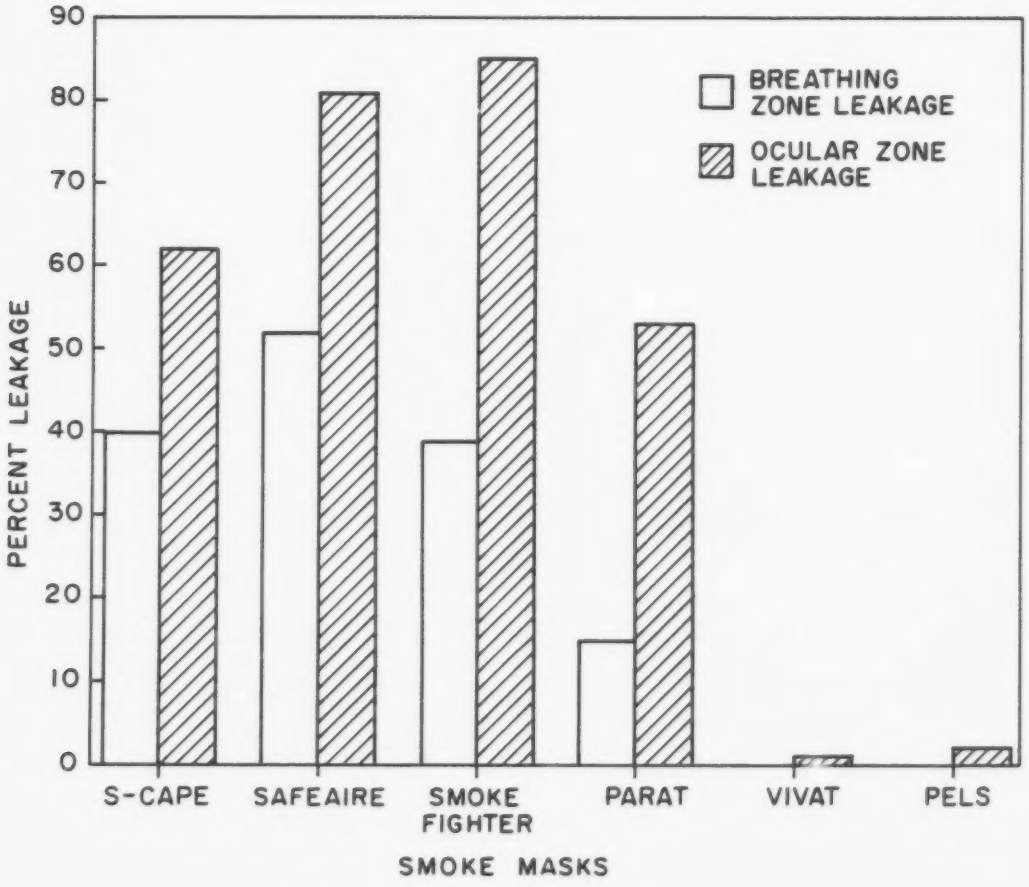
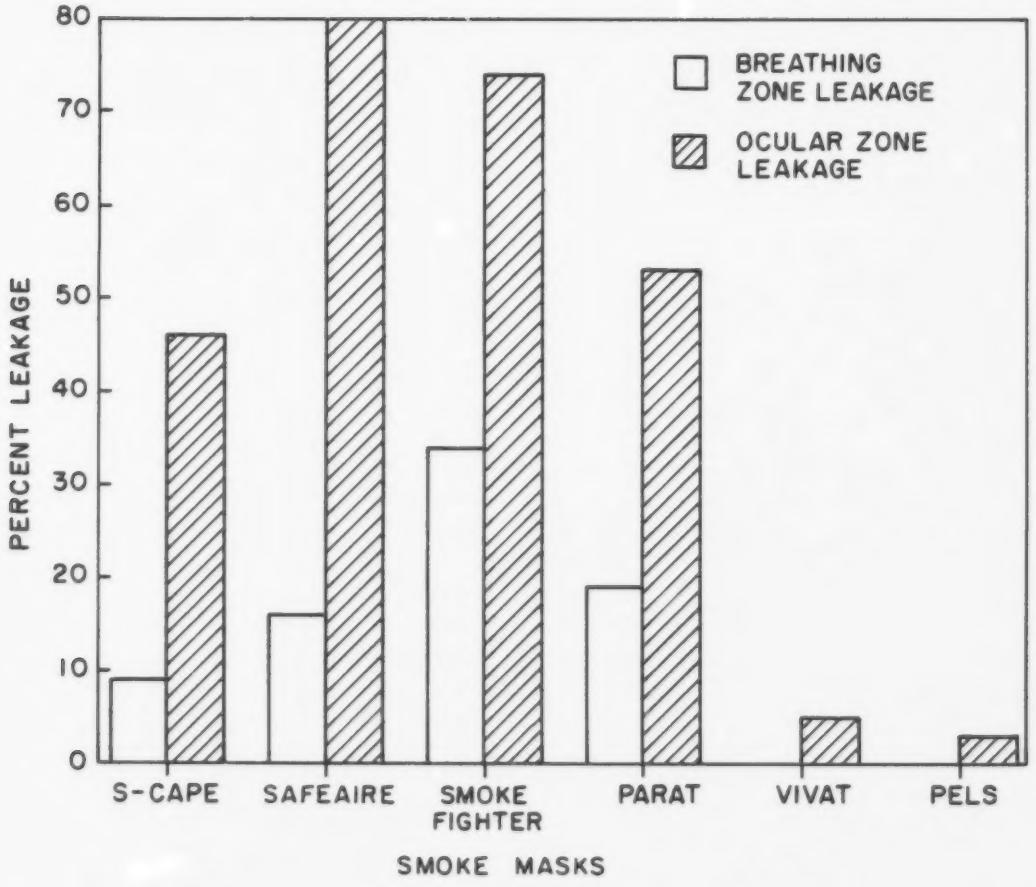


NOTE: FOR THE VIVAT AND PELS DEVICES, THE EDGE LEAKAGES INTO THE BREATHING AND OCULAR ZONES ARE EQUIVALENT.

FIGURE 5: SMOKE MASK EDGE LEAKAGE RESULTS - FEMALE SUBJECTS



NOTE: FOR THE VIVAT AND PELS DEVICES, THE EDGE LEAKAGES INTO THE BREATHING AND OCULAR ZONES ARE EQUIVALENT.

FIGURE 6 : SMOKE MASK EDGE LEAKAGE RESULTS - MALE SUBJECTS

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4.1.1 Vivat Escape Mask

The edge leakage results for the Vivat are consistent with the manufacturer's data[30] and with the work of McFadden et al[21]. It is interesting that female subjects had lower average leakage than male subjects (1% compared to 3%). This is probably due to their lower tidal volumes which results in less pumping, inflating and collapsing, of the hood. Pumping involves higher rates of leakage.[21]

It was obvious that there were elevated CO_2 levels in the Vivat during testing. Subject discomfort was such that only 5 subjects would agree to participate in the leakage tests. In addition, we had to reduce the duration of each edge leakage test by half to minimize subject discomfort and eliminate the "talking" exercise activity.

4.1.2 PELS System

The low leakage results were consistent with the work of McFadden et al[21] and with the manufacturer's data.[31] In addition to the tight neck seal, the supply of oxygen maintained the hood under positive pressure which would contribute to low edge leakage. Edge leakage for females was slightly lower than it was for males (2% compared to 3%).

4.1.3 Smokefighter

The mouth leakage results for the Smokefighter were initially thought to be too high. One would assume that the mouth and lips would provide a good seal on the mouthpiece. However, the following two factors resulted in leakage:

1. the breathing resistance of the Smokefighter filter is high, and

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2. the mouthpiece is large and inflexible.

Due to these factors most test subjects had to contort their mouths in such a way that there were small but visible openings at the corner of the lips. Some of the female subjects found it too difficult to breathe through the filter. Due to the imperfect seal of the goggles it was also easier to breath through the nose and this resulted in high levels of leakage.

4.1.4 Parat Mask

The average mouth leakage of the Parat was 15% which was lowest among devices utilizing internal facepieces. Indeed, the Parat facepiece was the most pliable in conforming to the human face. Because of this, there was relatively little difference between the results for male and female subjects. In fact, for the Parat, unlike the Safeaire and S-cape, female subjects had a lower average mouth leakage than male subjects (13% compared to 19%).

Most of the subjects experienced moderate to severe discomfort during the test. This was due to the following:

- the filter unit became extremely hot during the test,
- the high breathing resistance of the filter and lack of an exhalation valve, and
- the relatively high CO_2 levels.

Three of the female subjects felt physically ill following the tests. Their symptoms included dizziness, nausea and headaches. Two

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other subjects were under such distress that they panicked and removed the hood before the end of the test in order to "get some fresh air".

The hood leakage results were uniformly high and averaged 53%. The high hood leakage occurs because the neck seal is of cloth and hood material is sewn together.

4.1.5 S-cape Hood

The average mouth leakage for the S-cape was 24%. Males had much lower mouth leakage than females (9% compared to 40%). Several of the female subjects found it was difficult to obtain a good seal because the S-cape internal facepiece was too large for their faces. By contrast, 3 of 5 male subjects achieved excellent fits of 2% or less. For the bearded male subject, the mouth leakage was 16%.

The S-cape average hood leakage was 54%. The results for all subjects are uniformly high. This was expected as there is no neck seal and the hood material hangs loosely on the wearer's shoulders. The hood leakage for the S-cape was significantly lower than for the Safeaire though the hoods are very similar in design. This was probably due to the fact that the S-cape exhalation value exhausts into the hood thus providing a small degree of fresh air purging.

4.1.6 Safeaire

The average mouth leakage for the Safeaire was 33%. As was the case for the S-cape, mouth leakage for male subjects was much lower than it was for female subjects (16% compared to 52%). For three of the female subjects the leakage was well over 80%. Only two of the male subjects

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were able to achieve a relatively good seal (6% and 7%, respectively). The major reason for the high mouth leakage results was the awkward shape of the Safeaire internal facepiece. It was too narrow and stiff to mould to the human face. Significantly better facial fit could be achieved if the Safeaire were fitted with a more effective facepiece.

The hood leakage was consistently high and averaged 81%. As with the S-cape this was because there is no hood neck seal. The hood hangs loosely about the subject's shoulders.

4.1.7 Summary

The BSI draft standard[1] specifies that mouth and hood leakage must not exceed 2% and 10%, respectively. The FAA's draft TSO-C99[2] regarding protective breathing for the flight crew specifies mouth and hood leakage standards of 5% and 10%, respectively. Only the PELS System met both of these guidelines. The Vivat device satisfied TSO C-99 guidelines and came very close to satisfying the BSI requirements. None of the remaining devices were able to satisfy either the BSI or TSO-C99 guidelines.

4.2 Smoke and Toxic Gas Penetration

All candidate smoke masks utilizing filtration had smoke and toxic gas penetration data provided by the manufacturer or independent organizations. Table 6 summarizes the filter penetration data. This data indicates that the filtration units effectively filter the majority of the test gases.

The BSI draft standard[1] specifies that filtration devices shall have minimum penetration times of 15 minutes when tested against HCl, HCN,

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TABLE 6

Fire Gas Penetration:
Filtration Systems

Smoke Mask (min)	Test Gas	Flourate (l/min)	T (°C)	RH (%)	Test Gas Level (ppm)	Breakthrough Level (ppm)	Time to Breakthrough
Smoke-fighter	Total Hydrocarbon	5	Room T	not given	1000	100	15
	HCl	5	Room T	not given	300-500	10	60
	Particulate	5	Room T	not given	not reported	-	No penetration detected after 60 minutes
	CO	5	Room T	not given	3000	-	0, system does not filter CO
Safeaire	Co	30	30	50	5000	500	20
	SO_2	30	30	50	200	0.5	30
	H_2S	30	30	50	600	2	30
	Acrolein	30	30	50	94-105	5	22
Vivat	HCl	30	Room T	80	280 mg/m^3	10 mg/m^3	20
	TDI, MOI	30	Room T	80	140 mg/m^3	10 mg/m^3	60
	Acrolein	30	Room T	80	250 mg/m^3	10 mg/m^3	25
	Phosgene	30	Room T	80	200 mg/m^3	10 mg/m^3	30
	Formaldehyde	30	Room T	80	12 mg/m^3	10 mg/m^3	25
	Acetic Acid	30	Room T	80	250 mg/m^3	10 mg/m^3	30
Parat	CO	30	20	75	2500	150	> 15

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TABLE 6 (cont'd)

Fire Gas Penetration:
Filtration Systems

Smoke Mask (min)	Test Gas	Flowrate (l/min)	T (^{o}C)	RH (%)	Test Gas Level (ppm)	Breakthrough Level (ppm)	Time to Breakthrough
	CCl_4	30	20	75	1000	10	5
	Cl_2	30	20	75	1000	1	7
	HCN	30	20	75	1000	10	>120
	H_2S	30	20	75	1000	10	>120
	SO_2	30	20	75	1000	5	45
	NH_3	30	20	75	1000	25	>120
	HCl	30	20	75	1000	5	78
	NO_x	30	20	75	1000	5	> 15
	Particulate	95	20	-	20	-	penetration was 0.23%
S-cape	CO	30	Room T	20.7 g/m^3 absolute humidity	2500	150	26
	CCl_4	30	Room T	"	2500	10	31
	Cl_2	30	Room T	"	2500	1	32
	HCN	30	Room T	"	10	>120	
	H_2S	30	Room T	"	2500	10	>120
	SO_2	30	Room T	"	2500	5	37
	NH_3	30	Room T	"	2500	25	47
	HCl	30	Room T	"	2500	5	>120
	Particulate	95	20	"	20 mg/m^3	-	penetration was 0.57%

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acrolein and CO as outlined in Table 3. Although all the manufacturers have not measured penetration times for the gases BSI recommends, their testing was comprehensive enough to permit the following evaluations:

- the Parat, S-cape and Safeaire devices satisfy the BSI requirements, and
- the Vivat and Smokefighter do not filter CO and hence do not satisfy the BSI guidelines.

4.3 Condition of Inhaled Air

Figure 7 summarizes the results of the condition of inhaled air testing. For each mask, the average CO_2, oxygen and temperature levels are displayed.

4.3.1 Vivat

The highest CO_2 levels were observed in the testing of the Vivat device. CO_2 levels for subjects at rest averaged 3.9%. CO_2 levels for subjects under a 50 watt workload averaged 3.8%. One subject, had to discontinue the 50 watt test after 3 minutes. The CO_2 level had reached 7% and the subject was experiencing severe discomfort.

Oxygen levels averaged between roughly 16 and 18% for all test subjects and workloads. All subjects experienced a significant degree of discomfort while wearing the Vivat hood. Their symptoms, fatigue, dizziness and hyperventilation, were consistent with exposure to high CO_2 levels and anoxia. Temperature levels in the hood averaged 26.4°C at rest and 27.4°C under exercise.

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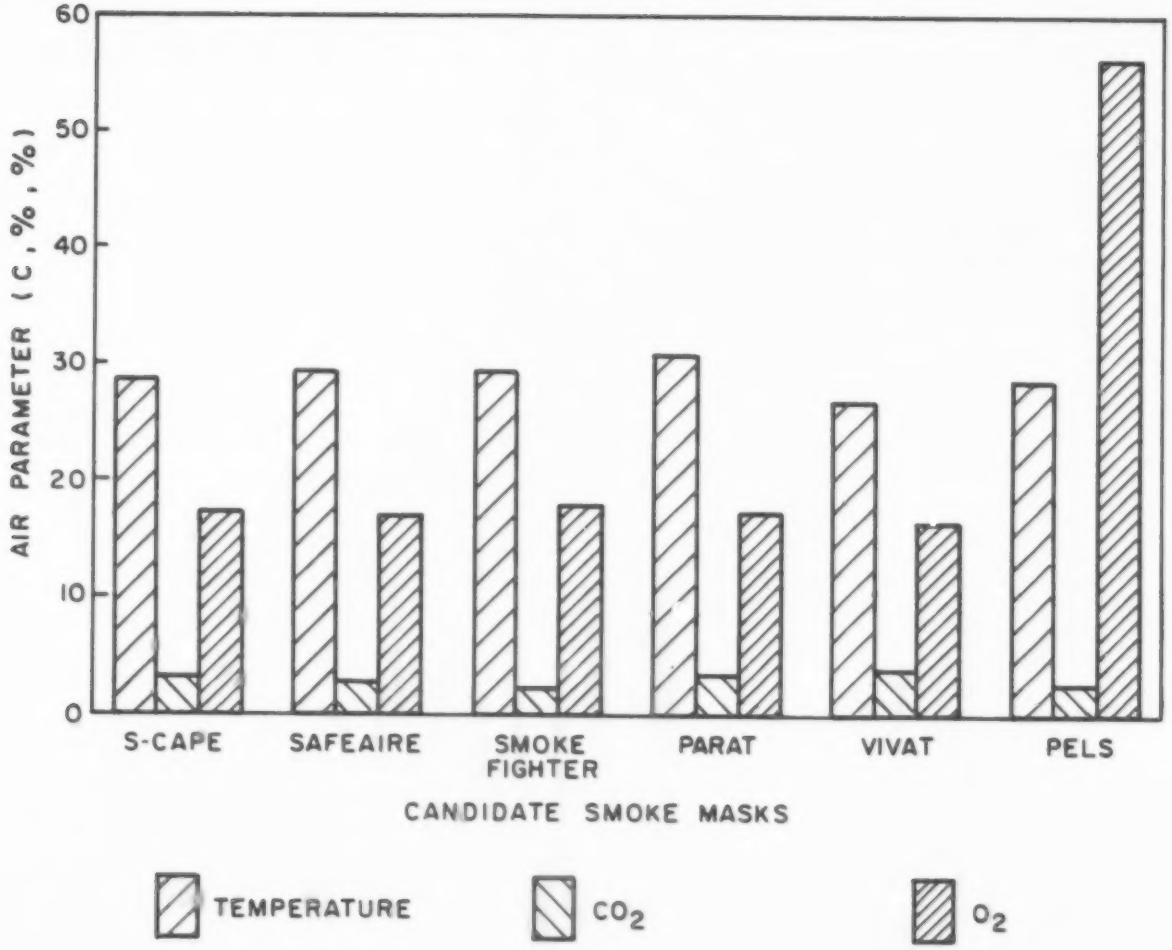

FIGURE 7: CONDITION OF INHALED AIR - ALL SUBJECTS

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The reason for the elevated CO_2 and depleted O_2 levels is because of the large internal volume of the Vivat hood. The test subject inhaled and exhaled the air within the hood and, consequently, there was insufficient intake of fresh air. Under these conditions, CO_2 levels rise steadily, while O_2 levels are depleted. The process is then self-correcting to some extent, since CO_2 elevation triggers deeper breathing which in turn results in more fresh air intake and dilution of CO_2 levels.

As a result of these tests, the manufacturer is reported to be studying methods of reducing the hood volume of the Vivat.

4.3.2 PELS System

Only 3 PELS System units were available to the project team. Thus, only 3, instead of 5, subjects were be tested. In addition, each hood was used twice, even though they are designed for a single use. After the first test the hoods were purged with fresh air prior to conducting the second tests. Each hood contained approximately 75g of LiOH. The duration of each test was 20 minutes.

The test results were favourable. Two of the three subjects were able to wear the PELS System with little discomfort during both the rest and workload tests. The third subject had no difficulty during the rest activity test but had to stop exercising midway through the 50 watt activity test due to rising CO_2 and temperature levels.

Oxygen levels in all tests were much higher than ambient levels and generally ranged between 40 and 70%.

In three of the six tests, temperatures in excess of 30°C were

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reached. This is due to the exothermicity of the reaction between LiOH and CO_2. The test subjects found the high temperatures somewhat uncomfortable but not intolerable.

In all tests, there was a great deal of condensation on the inside of the hood which totally obscured vision. Dupont is experimenting with anti-fogging solutions to correct this.

Subsequent to these tests, project team members witnessed further testing of the PELS System at Dupont laboratories. Four test subjects in all were used. They were all men, between 35 and 50 years of age. The quantity of LiOH per hood was varied through the test program. The activity regimen of each test subject was as follows: at rest for approximately 30 minutes, followed by several minutes of walking. Oxygen flowrates to the hood were also varied to gauge their effect. The following flow patterns were tested:

- 14 l/min for the first minute, 2 l/min for the next 14 minutes, (42 litres of oxygen total),
- fully inflating hood with oxygen at the start of the test (approximately 20 litres of oxygen in total) and then discontinuing flow, and
- 1.5 l/min for 15 minutes (22.5 litres of oxygen in total).

The results of these Dupont tests were also favourable and may be summarized as follows:

- the limiting factor determining how long the PELS System may be worn is the hood CO_2 level,

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- all test subjects were able to wear the hood for more than 30 minutes without excessive discomfort under all oxygen flow patterns,

- generally, CO_2 levels were in the range of 1 to 3% until the subject began walking, whereupon they exceeded 3%,

- the hood had almost fully collapsed and "pumping" of the hood was evident in most tests after approximately 25 minutes, and

- there was no noted difference in the ability to remove CO_2 between hoods with 50 g of LiOH and those with 75 g of LiOH.

The latter result is an important one, in that hoods with 50g as opposed to 75g of LiOH are significantly lighter (247g compared to 290g) and more compact.

4.3.3 Smokefighter

CO_2 levels for all tests were relatively low and averaged between 2 and 3%. Oxygen levels were generally in the range 18 to 19%. Temperature levels were generally less than $30^{o}C$. None of the five subjects experienced any significant discomfort due to CO_2, O_2 or temperature levels. However, all the subjects found that it was tiring to breathe through the Smokefighter.

4.3.4 Parat Mask

Temperature levels well in excess of $30^{o}C$ were measured during the Parat tests. This is due to the exothermicity of the catalyst in the

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filter. In fact, even higher temperatures may be expected since most of the catalyst had already been spent when the condition of inhaled air tests were conducted.

CO_2 levels were also high, averaging between 3 and 4% for most tests. This is due to the relatively large volume of the internal facepiece which trapped exhaled air. The subjects had to first inhale the stale air before fresh air could be inhaled through the filter into the facepiece.

For this same reason, oxygen levels are somewhat depressed and average between 17 and 18%.

4.3.5 S-cape Hood

The results for the S-cape hood are similar to those for the Parat with a few exceptions: the filter unit did not become hot and temperature levels were considerably lower.

CO_2 levels were also generally lower. This is because the S-cape is equipped with an exhalation valve. The subject does not tire as quickly, therefore, and is able to draw larger quantities of fresh air into the facepiece through the filter with each inhalation. Subjects experienced little discomfort while wearing the S-cape.

Oxygen levels in the facepiece ranged between 17 and 18%.

For all systems utilizing filtration, the CO_2 and oxygen levels in inhaled air depend strongly on the minute volume (i.e. the volume of air inhaled per minute) of the subject. Subjects with small minute volumes will tend to have higher CO_2 and lower oxygen levels in

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the breathing zone. Subjects with high minute volumes will purge the mask of stale air more effectively and thus will have relatively lower CO_2 and higher oxygen levels.

4.3.6 Safeaire Hood

For the Safeaire hood CO_2, oxygen and temperature levels were similar to those found in the S-cape. CO_2 levels ranged between 2 and 3%, oxygen levels between 17 and 18% and temperature levels were between 26 and 30°C. Little discomfort was experienced by test subjects. The exhalation value made breathing through the filter relatively easy.

4.3.7 Summary

The BSI draft standard[1] specifies that CO_2 and temperature levels in inhaled air shall not exceed 3% and 90°C (dry bulb), respectively. All the candidate smoke masks satisfy the temperature requirement. None satisfy the CO_2 requirement. For all candidate devices, CO_2 levels frequently exceeded 3%. However, only for the Vivat and Parat were CO_2 levels high enough to cause test subjects to discontinue the test. Most subjects appeared to be able to tolerate CO_2 levels of between 3 and 4% without excessive discomfort. Only when CO_2 levels rose to the 4 to 5% level was severe discomfort noted.

4.4 Ease of Donning

The ease of donning results are summarized in Table 7. The Vivat, PELS System, Smokefighter, S-cape and Safeaire were very easy to unpack. These devices are factory-sealed in foil or plastic and

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TABLE 7

Results of Ease of Donning Tests

Smoke Mask	No. of Subjects	Average Donning Time (sec)	Range (sec)	Standard Deviation (sec)
Vivat	9	5.4	3-9	2.1
PELS II	3	6.0	5-7	-
Smokefighter	10	9.7	5.5-15	3.1
Parat	10	9.3	4-18	4.2
S-cape	10	7.2	5-14	2.7
Safeaire	10	9.2	6-15	2.5

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unpacking simply involves ripping open the package. Subjects could generally do this in less than 5 seconds. The Parat device was somewhat more difficult to unpack. It is packaged in an aluminum cylinder with a pull-open top. Subjects could successfully remove the Parat from the package in less than ten seconds. It took longer to unpack the Parat because of the unusual package and because the mask had a tendency to "stick" in the cylinder. Unpacking the candidate devices would add 5 to 10 seconds to the measured donning times.

Subjects had little difficulty donning the candidate smoke masks. The average donning times for all devices were less than 10 seconds. In only one test did the donning time exceed 15 seconds.

The systems having hoods with neck seals, i.e., the Vivat and the PELS System, took the least time to don. The devices having hoods and facepieces, i.e., the S-cape, Safeaire and Parat, were next in order. The Smokefighter had the highest average donning time, but the net difference compared to the Vivat was only 4.2 seconds.

The results of the subject questionnaires, generally, corroborate this statement. Subjects reported that they had only minor difficulties donning the candidate devices. In addition, they had the following subjective responses to each device.

4.4.1 Vivat Mask

Three of nine subjects expressed reservations over putting a "plastic bag" over their heads, although indicated that they would do so in an emergency situation. Two of nine subjects also commented on the "bad smell" inside the Vivat hood.

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4.4.2 PELS System

One of three test subjects expressed a reluctance to put a "plastic bag" over her head but, again, felt she would do so in an emergency situation. There were no other negative comments expressed in the questionnaires.

4.4.3 Smokefighter

Five of ten subjects found that the mouthpiece was too large for the mouth. Three of ten subjects found that the device was quite heavy and that their jaws were tired after a few minutes. All subjects found that it was impossible to swallow while wearing the Smokefighter and that as a result it was difficult to prevent saliva from spilling out of the mouthpiece and the subjects' mouths.

4.4.4 Parat Mask

All ten subjects experienced moderate to severe discomfort while wearing the Parat. Complaints centred on excessive heat, breathing resistance, claustrophobia and odour. Most subjects felt dizzy after several minutes. Two subjects panicked and removed the hood almost immediately in order "to get some fresh air". They expressed serious doubt as to whether they would wear the Parat even in an emergency.

4.4.5 S-cape Hood

Three of ten subjects found that the S-cape facepiece was moderately heavy and that it "pulled down" on the nose. Two of five female subjects felt that the S-cape facepiece was too large for their faces.

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It is noteworthy that none of the subjects experienced severe discomfort as they did with the Parat, even though the two masks are similar in design. The S-cape differs from the Parat in that it has an exhalation valve and the filter does not overheat.

4.4.6 Safeaire Hood

Eight of ten subjects found it difficult to achieve a good seal with the Safeaire facepiece. They felt that the facepiece was improperly shaped and/or that the drawstring was difficult to pull tight. Some of the gaps between the face and facepiece were so large that subjects were able to put their fingers through them. Those subjects that were able to pull the drawstring tight, found that the facepiece pinched the nose painfully.

4.4.7 Summary

Draft TSO C-99[2] specifies that donning times for flight crew protective breathing equipment must not exceed 15 seconds. In general all candidate smoke masks meet the TSO C-99 guideline with the exception of the Parat mask. Because of the somewhat unusual packaging, donning times for some people could exceed 15 seconds.

4.5 Vision and Vocal Communication

In general all candidate smoke masks satisfied the BSI vision and communication tests. Specific results are as follows:

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4.5.1 Vivat Mask

All nine subjects were able to read the exit sign with letters 6 inches high at a distance of 10 metres. Three subjects felt that their vision was slightly distorted by the kapton material. Some condensation was observed on the inside of the hood during the 50 watt exercise test, but not enough to significantly obscure vision.

Subjects had no trouble vocally communicating with the scientist while wearing the hood.

4.5.2 PELS System

For all 3 test subjects, there was considerable condensation on the inside of the hood. After 10 to 15 minutes, depending on the subject, vision was totally obscured.

Test subjects had no trouble with vocal communication while wearing the PELS System.

4.5.3 Smokefighter

All 10 subjects were able to read the exit sign without any difficulty. For 3 of 10 subjects, condensation was noted on the inside of the goggles. This partially obscured vision. Two of 10 subjects noted that their vision was somewhat distorted by the goggle material.

None of the 10 subjects were able to vocally communicate with the scientist unless they removed the mouthpiece. It was not clear to the subjects whether it was acceptable to remove the mouthpiece to talk. This was not emphasized in the instructions by the scientist.

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4.5.4 Parat Mask

Nine of ten subjects could read the exit sign with no difficulty. One subject could not because his glasses came off while donning the hood.

All subjects could vocally communicate with the scientist while wearing the hood even though their voices were somewhat muffled.

4.5.5 S-cape

All subjects were able to read the exit sign at a distance of 10 metres with no difficulty. They were also all able to vocally communicate with the scientist though their voices were somewhat muffled.

4.5.6 Safeaire Hood

Eight of ten subjects experienced moderate to severe vision distortion while wearing the Safeaire mask. One subject compared wearing the mask to "wearing someone else's glasses". They were still able to read the exit sign from a distance of 10 metres, however.

All ten subjects were able to vocally communicate with the scientist though the facepiece muffled their voices somewhat.

4.5.7 Summary

In all tests, except one, the smoke masks satisfied the BSI vision and communication requirements. In the one test that failed the subject's glasses accidently dislogded during donning of the mask.

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TABLE 8

Results of Breathing Resistance Tests

Smoke Mask	Breathing Resistance (in H_2O)		Recommended Level (in. H_2O)[1]	
	Inhalation	Exhalation	Inhalation	Exhalation
Parat	0.37	0.35	3.76	1.41
	0.36	0.34		
	0.35	0.33		
S-cape	0.59	-	3.76	1.41
	0.60	-		
	0.61	-		
Smokefighter	1.85	-	3.76	1.41
	1.88	-		
	1.90	-		
Safeaire	1.00	-	3.76	1.41
	1.20	-		
	1.40	-		
Vivat	0.11	0.065	3.76	1.41
	0.11	0.061		
	0.10	0.065		

Note: Flowrates were approximately 30 l/min (STP)
Exhalation resistance was not measured for smoke masks having exhalation valves.

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4.6 Breathing Resistance

The results of the breathing resistance tests are summarized in Table 8. Flowrates of approximately 30 l/min were drawn through the filters. Three samples of each smoke mask were tested. Exhalation resistance was not measured for masks having exhalation valves (i.e. S-cape, Smokefighter and Safeaire).

Due to the awkward shape of the Vivat filter, the breathing resistance test had to be modified somewhat for this device. The filter was too large to be connected to the airflow duct. Instead, a circle of 5.5 cm diameter was cut from the filter and connected to the airflow duct. Flowrates were adjusted so that the velocity at the face of the filter was approximately 168 cm/s. This face velocity corresponds to a flowrate of 30 l/min through the entire face of the filter. Pressure drop across a fabric filter is proportional to the face velocity.

All results are well below the levels recommended in the draft BSI standard. The Smokefighter had the highest inhalation resistance of all the masks tested. During the edge leakage and the condition of inhaled air tests the Smokefighter was perceived as having relatively high breathing resistance. It ranged from 1.85 to 1.90 inches of water for this device. The Vivat device had the lowest breathing resistance results. This is due to the relatively large surface area of the filter material.

It is noteworthy that test subjects perceived the Parat mask as having the highest breathing resistance during the edge leakage and condition of inhaled air tests even though its inhalation resistance was the lowest except for the Vivat. This is probably due to the lack of an exhalation valve and also to the relatively good facial seal of the facepiece. The subjects inhale more of their minute volumes through the

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filter and less through leaks. By contrast, the Safeaire device which had a relatively less effective facepiece seal had the second highest inhalation resistance, and test subjects did not perceive it as having a high breathing resistance. The facial seal with this device was not as good as for the Parat and test subjects drew proportionately less of their minute volumes through the Safeaire filters.

The BSI draft standard on smoke masks[1] specifies that resistance to breathing imposed by these devices shall not exceed 3.76 inches of water (8 mbar) inhalation and 1.41 inches of water (3 mbar) exhalation. All candidate smoke masks meet these criteria.

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5. DISCUSSION OF TESTS

5.1 Edge Leakage Criteria

The test protocol developed for measuring edge leakage satisfactorily quantified the degree of edge leakage of gases into both the breathing zone and the ocular zone of the smoke masks. The provision of real-time measurement also allowed interpretation of the data to determine the factors which were contributing to edge leakage. In a few instances the time duration of the tests had to be shortened. This was not because the test protocol time period was unsuitable but because the smoke masks were of unsuitable design. Levels of CO_2 increased to the point that subjects could no longer continue the tests.

Only the PELS System smoke mask met the BSI draft standard of 2% in the breathing zone and 10% in the ocular zone. The BSI specification for edge leakage may be overly stringent. In occupational health applications, edge leakage levels in the order of 10% for filtration devices are considered satisfactory. The TSO-C99 guideline of 5% and 10% for the breathing zone and ocular zone, respectively, is more realistic for passenger populations. This TSO-C99 guideline was met by two of the six smoke masks tested.

This method of edge leakage measurement uses a tracer gas to evaluate leakage. A fire environment also contains a large quantity of airborne particulate matter. It is not known whether airborne particulate would behave in a similar manner to the tracer gas and, therefore, whether tracer gas edge leakage results are representative of fire particulate edge leakage.

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5.2 Smoke and Toxic Gas Penetration Criteria

The manufacturer information indicates that this factor can be determined and that breakthrough times of greater than 15 minutes can be obtained. In some instances, filtration devices did not provide provision for carbon monoxide removal. There is debate over whether CO is a critical factor which contributes to incapacitation in passenger aircraft fires. Considering the uncertainties of carbon monoxide's role in incapacitation and the many differences in passenger aircraft fires which have and could occur, it is recommended that CO be included in the list of toxic gases which require control.

5.3 Condition of Inhaled Air Criteria

The test protocol developed for measuring the condition of the inhaled air also satisfactorily quantified the levels of CO_2, O_2 and the temperature of the inhaled air. The real-time measurement of these parameters was a very useful factor in interpreting the results. Although the subjects complained of discomfort due to high temperature, none considered the levels dangerous. However, the high CO_2 levels encountered, greater than 4%, did result in subject discomfort and in various circumstances termination of the tests. Real-time measurement as a safety precaution should be followed in order to alert test operators of dangerous test subjects exposures.

Test subjects experienced discomfort only when carbon dioxide levels exceeded 4% and not 3%, the BSI draft level. Since the subjects of this study were healthy and did not include the young or old, a concentration of 3% carbon dioxide should still be considered a maximum level.

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5.4 Ease of Donning Criteria

The test protocol for evaluating the ease of donning various smoke masks satisfactorily quantified the donning times and documented the opinions of subjects on donning and wearing the smoke masks.

5.5 Vision and Vocal Communication Criteria

The simple vision and vocal communication protocols adopted from the BSI draft[1] may be overly simplistic. The test protocol does not represent a smoke filled environment, the "exit" sign, which requires identification, was known by the subjects to be an "exit" sign prior to the test, and the communication test protocol is qualitative not quantitative.

5.6 Breathing Resistance Criteria

The protocol used to measure filter breathing resistance satisfactorily quantified the pressure drop across the filter units. All of the measured pressures were less than the BSI draft[1] level of 8 mbar (3.76 inches) of water inhalation and 3 mbar (1.41 inches) of water exhalation. Even though the smoke masks met the BSI draft standard, problems were identified with two smoke masks as a result of high breathing resistance: the Parat hood experienced high CO_2 levels and the Smokefighter experienced edge leakage, both of which were due to filter breathing resistance. The Parat and the Smokefighter were also perceived by the subjects during the edge leakage and condition of inhaled air tests of having high breathing resistance.

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5.7 Protection from Inhalation Incapacitation

As previously mentioned, the purpose of an airline passenger smoke mask is to protect passengers against inhalation incapacitation for short periods of time to permit evacuation from a passenger aircraft fire. In order to reduce a large number of influencing factors such as toxic constituents behaviour in fires and the protective capability of a smoke mask, into a single parameter, such as time-to-incapacitation, the FED model[11] can be used. This model is useful in assessing a candidate mask's ability to provide protection. A key factor in this model is the protection factor term (Pi) which quantifies the protection provided by a mask to toxic species "i". A protection factor term may be determined from results of edge leakage and filtration tests. In this study, edge leakage was the dominant factor in determining the protection factor. Even though filtration protection was good, the edge leakage was high and the result ratio of the breathing zone toxic gas concentration to the cabin toxic gas concentration, the protection factor, was high. Carbon monoxide protection factors were also influenced by two of the masks' inability to filter CO. Protection factors derived from the tests on the six candidate smoke masks for various toxic fire gases are presented in Figure 8. Data in Figure 8 indicates that protection factors are often greater than 0.1, or the smoke masks provide, in most instances, less than 90% protection from toxic fire gases and, therefore, are unsatisfactory.

5.8 Summary of Smoke Mask Evaluations

A summary of the evaluation tests on the six smoke masks is presented in Table 9. Even though none of the six candidate smoke masks met all of the criteria, various good design concepts were identified.

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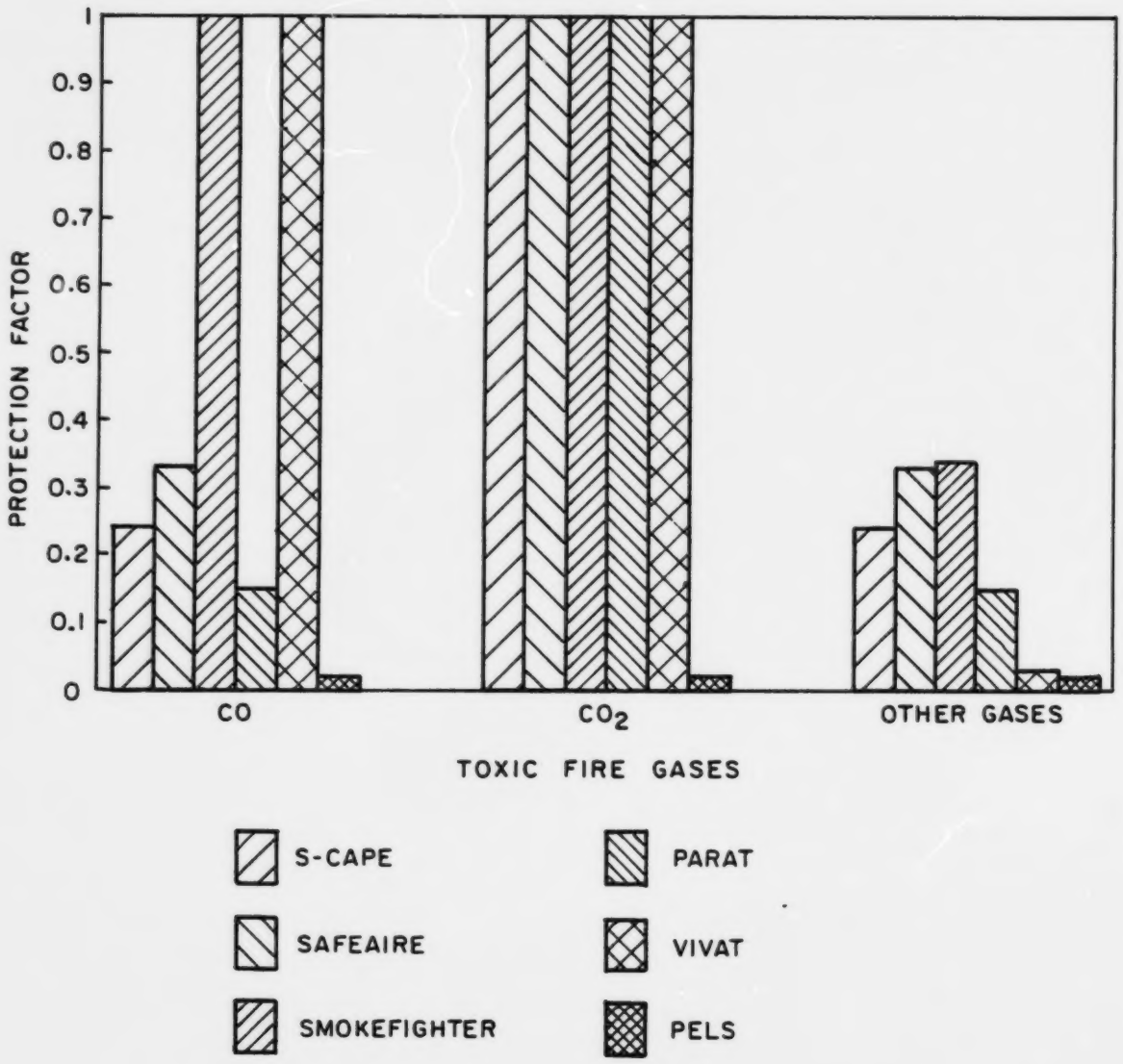

FIGURE 8: SMOKE MASK PROTECTION FACTORS

The silicon or rubber neck seals of the PELS system and the Vivat successfully provide seals with edge leakages below 5 percent. The knit neck seal of the Parat was unsuccessful in preventing edge leakage.

The facepieces of the Parat, S-cape and Safeaire did not provide adequate seals and therefore had high edge leakages. It is extremely difficult to design one facepiece which will provide a good seal for all possible face shapes. The Parat has a comfortable, pliable facepiece but still was only able to obtain an average mouth edge leakage of 15 percent. The facepieces of the S-cape and the Safeaire were large and awkward and had even greater mouth edge leakages.

The Smokefighter, with a mouthpiece/goggles design did not meet the edge leakage criterion because the mouthpiece was too large and distorted the subjects' lips.

Filtration systems are capable of removing toxic gases and smoke. The Vivat and Smokefighter failed only because they were not designed to remove CO. These two smoke masks could be easily modified to provide CO removal.

The PELS with oxygen supply and CO_2 removal can successfully provide an acceptable environment within the mask. The Vivat which does not have a CO_2 removal system but relies on inhaling fresh air through a filter failed the condition of inhaled air tests. Modifications to the Vivat to ensure the intake of fresh air through the filter and exhalation of stale air through an exhalation valve could possibly solve this problem.

The Parat, which does not have an exhalation valve, experienced problems of high CO_2 and discomforting high temperature. Carbon

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TABLE 9

Summary of Smoke Mask Evaluation Tests

Smoke Mask	Evaluation Criteria: Edge Leakage	Smoke and Toxic Gas Penetration	Condition of Inhaled Air	Ease of Donning	Vision and Vocal Communication	Breathing Resistance	Comment
Vivat Mask	P	F	F	P	P	P	No CO removal, CO_2 in excess of 3%
PELS System	P	N.A.	F	P	F	N.A.	Condensation obscured vision, CO_2 in excess of 3% in on test
Smokefighter	F	F	P	P	F	P	Excessive leakage, no CO removal, mouthpiece must be removed to talk
Parat Mask	F	P	F	F	F	P	Excessive leakage, CO_2 in excess of 3%, donning time greater than 15 seconds, glasses dislodged - vision not possible
S-cape Hood	F	P	P	P	P	P	Excessive leakage
Safeaire	F	P	P	P	P	P	Excessive leakage

Notes: P = passed
F = failed
N.A. = not applicable

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dioxide was not adequately exhaled through the filter and the moisture of the exhaled air was reacting with the filter CO catalyst which resulted in high temperatures. Subsequent to these tests, Drager have installed an exhalation valve on the Parat masks.

The mouthpiece-filter configuration of the Smokefighter, which has an exhalation valve, met the condition of inhaled air criteria.

The hood designs of the Vivat and PELS had the shortest donning times as they required minimal adjustment to ensure proper fit. The facepiece/hood designs, Parat, S-cape and Safeaire, required facepiece adjustments which in one instance delayed donning beyond 15 seconds. The mouthpiece/goggles design, Smokefighter, was simple but adjustments to the goggles lengthened total smoke mask donning times.

Condensation in the PELS resulted in obscured vision and, in turn, failure of the vision criteria. Dupont are investigating coatings to be applied to the inner surface of the mask to solve this problem. The Vivat did not encounter condensation problems but the test times were shortened because of CO_2 buildup. If the test had been longer the Vivat may also have experienced condensation and obscured vision.

The facepiece/hood designs, Safeaire, Parat and S-cape, met the vision criteria except in one instance when a subject's glasses were dislodged during donning. All masks met the vocal communication criteria except the Smokefighter. In order to talk the mouthpiece must be removed.

All of the smoke masks met the breathing resistance criteria.

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6. FURTHER RESEARCH AND DEVELOPMENT

This study has reviewed existing standards and developed a set of preliminary criteria and test protocols for evaluating airline passenger protective breathing equipment. Six candidate emergency escape smoke masks were evaluated using these preliminary criteria and test protocols. Based on these evaluation tests, the following recommendations regarding further development of passenger airline protective breathing equipment performance criteria are presented.

An airborne particulate test protocol should be developed and tested on candidate smoke masks. The edge leakage test criteria developed in this study uses a tracer gas. It is not known whether the tracer gas edge leakage results are representative of fire particulate edge leakage.

Test subjects for this program did not include the young, the old or those with respiratory illnesses. Test subject selection criteria should be developed to include those representative of airline passengers.

As previously mentioned, the vision and communication criteria and test protocols were overly simplistic. More quantitative criteria and test protocols should be developed.

Further research is needed to determine filter pressure drops which adversly affect the performance of a smoke mask or are unacceptably discomforting to the wearer. The present BSI draft standard does not identify adverse smoke mask breathing resistance conditions.

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It is recommended that Federal Aviation Regulation 25.853 and Underwriters Laboratory Test 94 be evaluated with regards to their suitability as resistance to flame criteria.

In order to assess protection from inhalation incapacitation, a methodology should be developed to determine a smoke mask protection factor. This methodology would be based on the results of the tests for edge leakage, conditions of inhaled air, and smoke and toxic gas penetration.

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Appendix A

Test Subjects

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TABLE A1

Test Subjects

Subject Identification	Age	Sex	Height (cm)	Weight (kg)	Comments
1	28	F	157	62	-
2	21	F	170	57	-
3	39	M	185	72	-
4	35	M	180	82	glasses
5	28	F	173	61	-
6	26	F	155	47	-
7	28	M	173	68	glasses
8	27	F	165	59	-
9	21	M	175	75	-
10	28	M	173	67	-
11	19	M	175	64	-
12	40	M	175	82	beard
13	23	F	157	54	-
14	36	M	173	62	glasses
15	24	F	175	53	-
16	30	M	185	82	-
17	22	M	186	80	glasses

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